

ADVANCED UNDERGRADUATE LABORATORY

EXPERIMENT XX

SINGLE PHOTON DETECTION

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Single Photon Detection Module for Quantum Entanglement Apparatus

INTRODUCTION

The Undergraduate Advanced Physics Lab at the University of Toronto is introducing an apparatus capable of experimentally testing the predictions of quantum mechanics using entangled photons. It will serve the purpose of adding to the educational experience of students by allowing undergraduates in both Physics and Engineering Science to directly observe quantum mechanical phenomena taught to them in their other undergraduate courses. A single photon coincidence detection module has been developed as part of the first phase of building the entangled photon experiment apparatus. This walkthrough serves as an overview of the detection module as well as protocols on operating and testing the single photon detection, coincidence counting and LabVIEW data analysis for integration with the future experiment.

SINGLE PHOTON DETECTION MODULE OVERVIEW

The detection module is shown in Figure 1. It is used to register and interpret single and coincidence photon detection events relevant for future experiments. Single photon detection is performed when photons are incident on any of the four Avalanche Photodiodes (APDs). If photons arrive at the detectors within a specified coincidence window of time ($3ns - 20ns$) then they are considered coincident. Coincidence counting calculations are performed by hardware logic on an Altera DE2 Field-Programmable Gate Array (FPGA). The single detection counts, coincident detection counts and statistical counting errors are then reported to the user through a LabVIEW computer interface.

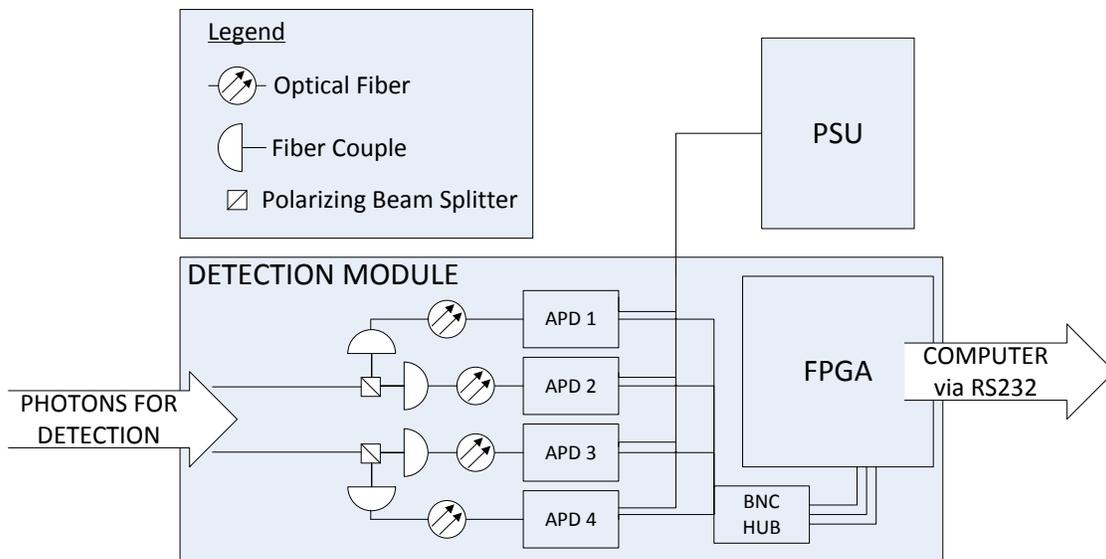


Figure 1 - Overview of the Detection Module

Components:

- FPGA: Altera DE2-115
- APDs: Excelitas SPCM-EDU CD3375H22332
- PSU: +5V/1.2A Power Supply Unit
- BNC Cable to 40-Pin Parallel Cable Connection HUB

- <3dB Multimode Fiber Optic Cables
- Fiber Coupling Stages, each contain:
 - 2x 1” Lens Tubes
 - Aspherical Coupling Lens (C220TME-B f=11.00mm)
 - Aperture Iris Shutter
 - Kinematic Table Mount

* The polarizing beam splitters are only required for specific experiments and have not yet been purchased.

** Only two Fiber Coupling Stages have been purchased thus far.

QUICK REFERENCE AND OPERATION PROTOCOLS

The following instructions should be followed to operate the Detection Module:

!!WARNING!!

- **RULE: If the PSU Red LED is ON then the Room lights are OFF.**
- **To prevent damage to sensitive and valuable components, READ AND FOLLOW all protocols before operating!**
- **To prevent overheating and possible damage due to diode saturation DO NOT power on APD units (PSU Red LED should be OFF) while the overhead room lights are on, room door is open or if the fiber optic cable is disconnected from the APD input port.**
- **Minimize ambient light when operating APDs and DO NOT exceed single counts of $2 \cdot 10^6$ for extended periods of time.**
- **Do not strain optical fibers by bending or twisting, this will change the propagation of light in the fiber and excessive strain will break the core.**

Turning the Detection Module ON

Beginning with all units turned completely off:

- (a) Inspect the apparatus and ensure the following:
 - i. Optical Fibers are connected securely between APDs and the Fiber Couplers.
 - ii. Rubber blackout caps are placed on all APDs not in use.
 - iii. Aperture Iris on each fiber coupler is closed.
 - iv. APDs are plugged into PSU and the power cables are connected Green-to-Green and Red-to-Blue.
 - v. FPGA Power Cable is plugged in.
 - vi. APD BNC Output ports are connected to A,B,C,D input port of the BNC HUB.
 - vii. 40-Pin parallel cable is connected between the FPGA and BNC HUB with orientation arrows aligned at each connector.
 - viii. RS232 cable is connected between the FPGA and PC computer.
 - ix. The 18 front-panel FPGA switches are all in down position and the RUN/PROG switch is in “RUN” position.
- (b) Power on the FPGA.
- (c) Power on Computer and open LabVIEW program.
- (d) Open file “Detection.vi” located on the Desktop.

- (e) Click the “RUN” button in LabVIEW to initiate the program.
- (f) Power off overhead room light and close the door.
- (g) Check for sources of ambient room light and minimize light scattering into the fiber couplers.
- (h) Power on the APD PSU (PSU Red LED should be ON).
- (i) Check that counts are being registered under Single Counts, Coincident Counts and Accidental Coincidences that are consistent with the APD configuration. (Rubber capped APDs should read dark counts of ~300 per second)

NOTE: The APD PSU also has a master power switch on the back of the unit and each power line is equipped with an independent fuse. Check these first when troubleshooting the PSU.

Switching to STANDBY Mode

The following assumes that the Detection Module was powered on according to the correct power protocols from the previous section.

- (a) Click the “STOP” button in LabVIEW to end the program.
- (b) Power off the APD PSU (PSU Red LED should be OFF).
- (c) Turn on overhead room lights.

Powering OFF

- (a) Follow “Switching to Standby Mode”.
- (b) Power off the FPGA.

Using the LabVIEW VI

The LabVIEW VI (Figure 2) is configured to display relevant single and coincident photon detection data. The program requires three input parameters: counter port, update period, and coincidence window. The counter port specifies which hardware component is in communication with the LabVIEW software (in this case, RS232). The update period is how often the displayed data is refreshed on the VI, and should be selected within increments of 0.1s.

Photon counts are shown on the LabVIEW VI for all single counts (corresponding to APD’s A, B, C, D) and coincidence counts occurring within the specified coincidence window. Coincidences are reported for all possible APD combinations. **The Coincidence Window should correspond to the Detection Timing Window selected on the FPGA** (See below for calibrating the timing window) otherwise data will be recorded incorrectly.

For coincidence counts, the VI displays 1) raw counts, 2) statistical corrections, and 3) corrected counts. The statistical correction accounts for “accidental coincidences” of classical photons and is calculated with the following formula:

$$C_S = \frac{2N_1N_2\tau}{T} \quad (1)$$

Where N_1 and N_2 are the counts read in each channel per update period T , and τ is the timing window. In this experiment, the timing window should directly correspond to the widths of the pulse. Although the LabVIEW program requires the user to input the timing window, it is hard to accurately estimate the timing window given by each pulse width. A calibration can be performed to accurately determine this window (see Experiment section).



Figure 2- LabVIEW GUI

1. RUN button (press only when the FPGA is on)
2. STOP button
3. Input settings: hardware port (COM1 for RS232, update period, and coincidence window)
4. Single photon counts
5. Coincidence counts: corrected coincidences, statistical correction, and raw coincidences
6. Warning light for “APD Light Level”
 - a. Warning light will turn red when the single count meters saturate, meaning an unsafe amount of light is picked up by any of the APD’s (over 1,000,000 photons). This is dangerous, as overexposure to light may saturate the APD’s. If this happens, turn the APD power off and check that not too much light is reaching the fiber couplers or APD inputs.
7. Graph for determining effective coincidence window (plot’s raw coincidence counts with expected statistical correction for AB coincidences)

Note: If the RUN button is pressed when the FPGA is off, LabVIEW receives an **error** due to not being able to detect any hardware. When this happens, press CONTINUE, and try again. This may also happen when toggling between ON and OFF on the LabVIEW VI. This error is due to the port not completing its configuration by the time the first character is received off the RS232 port.

Changing the Coincidence Detection Timing Window

The coincidence detection timing window is defined as the amount of time between detection events on independent APDs that will register as a valid coincidence count. The timing window directly corresponds to the widths of the pulses used for detecting coincidences. Thus to control the timing window, the pulse widths are controlled accordingly. The size of the timing window may be selected from $3ns - 20ns$ by configuring the front panel FPGA switches according to Table 1. Note that these pulse widths (and hence timing windows) were measured by the approximate Full-Width Half-Maximum (FWHM) of each pulse. These values are not necessarily the actual timing window that the FPGA produces, but are a good estimate. To

accurately determine this window, one can start with these values and then perform a calibration as indicated later in the experiment.

Table 1: Estimate of shortened pulse widths with switch selections.		
Switch Setting ("17;16;15;14;13")	Shortened Pulse Width [ns ± 0.1] (measured @ 2.5 V crossings)	Pulse Peak Voltage [V ± 0.05]
0: "00000"	14.45 (original pulse, no shortening)	5.2
1: "00001"	13.7	5.2
2: "00010"	13.35	5.1
3: "00011"	13.3	5.1
4: "00100"	12.9	5.1
5: "00101"	12.5	5.1
6: "00110"	12.25	5.1
7: "00111"	12.1	5.05
8: "01000"	11.8	5.05
9: "01001"	11.35	5.1
10: "01010"	11.2	5.1
11: "01011"	11.0	5.1
12: "01100"	10.85	5.1
13: "01101"	10.25	5.1
14: "01110"	9.9	5.1
15: "01111"	9.75	5.1
16: "10000"	9.45	5.05
17: "10001"	9.0	5.0
18: "10010"	8.7	4.9
19: "10011"	8.7	4.95
20: "10100"	8.2	4.85
21: "10101"	7.4	4.55
22: "10110"	6.95	4.35
23: "10111"	6.8	4.25
24: "11000"	6.65	4.15
25: "11001"	5.85	3.8
26: "11010"	5.4	3.55
27: "11011"	5.1	3.35
28: "11100"	4.45	3.15
29: "11101"	4.3 @ 2.2 V	2.75
30: "11110"	3.6 @ 2.2 V	2.55
31: "11111"	<2.9 @ 2.2 V	2.4

Replacing PSU Fuses

The APD PSU contains 1.5A fuses on each power line to prevent the APDs from damage due to saturation overcurrent. In the event that a fuse blows the APD will lose power and will be not read any single counts in LabVIEW. The fuses are located behind the front panel of the PSU and are easily replaced by removing the four screws from the face of the PSU panel.

Fiber Coupler Alignment

Incoming photons must be properly coupled to the fiber optics of the photon detectors. The coupling efficiency should be maximized by insuring that the coupling lens properly focuses the incident photons onto the core of the fiber. For instructions on performing fiber coupling see below. In addition to calibrating the correct focal length of the lens, the incident photon beam should arrive within an acceptance angle of $\pm 0.2^\circ$ to insure that the focal point remains laterally located on the fiber core.

To optimize coupling efficiency for one fiber coupling stage:

- (a) Ensure that the APD power is OFF.
- (b) Remove the front-most 1" lens tube and aperture iris from the end of the fiber coupling stage.
- (c) Disconnect one fiber optic cable from the face of the APD. Do not disconnect it from the fiber coupling stage.
- (d) Use the laser pointer to shine light into the butt end of the disconnected fiber.
- (e) Confirm the light is passing through the fiber by holding the alignment card (or white piece of paper) in front of the fiber coupler and observe the laser beam. If it is not seen, adjust the laser pointer. This may require two people.
- (f) Use the two-pronged SM1 adapter wrench to adjust the position of the coupling lens inside the remaining 1" lens tube and collimate the laser beam to a sharp point at least 5' or more away from the coupling stage. The wrench is used by inserting the prong-side into the 1" lens tube and aligning the prongs with two small holes in the lens mount. Turning the wrench will move the lens closer or further from the fiber core. The focal length of the lens is 11.00mm.
- (g) Reconnect the fiber cable to the APD and place the 1" lens tube with aperture iris back on the end of the fiber coupler stage.
- (h) Repeat for each fiber coupler stage.

Maximum Loading of APDs and Counting Logic

The **maximum** loading for the APDs is $10 \cdot 10^6$ counts per second, at which point it will output a DC signal and be **at significant risk of overheating**. The ideal maximum operating point is $2 \cdot 10^5$ after which thermal effects begin to affect count reliability. Thermal effects will cause diode breakdown where data will become unreliable at counts near and above $5 \cdot 10^6$. The counting logic of the FPGA has been tested at frequencies of 10 MHz and is not a limiting factor for detection speed of the apparatus. If the APDs are ever maximally loaded, the "APD Light Level" indicator on the LabVIEW VI will turn red and provide a warning. Immediately lower light levels or turn off APDs if this occurs and.

EXPERIMENT (for Walkthrough)

1. Turn on and Verify Basic Functionality.

Goal: Verify that everything is connected properly. Also verify that the counts picked up from the APDs with blackout caps correspond to the dark count given by the APD datasheet.

What you need to know:

The blackout caps that cover the input to the APDs are very good at blocking out any light.

With these caps on, the APDs should output counts corresponding to the dark count of the detector. The datasheet for the APDs gives a measured dark count of ~ 278 with a maximum dark count of 4000.

Procedure:

- (a) Connect all APD outputs to the appropriate channels of the BNC HUB.
- (b) Turn everything on according to the ON Procedure.
- (c) Verify that counts are being picked up on the individual count meters. Note that the occasional coincidence appears in the coincidence meters. Also, ensure that the light level indicator is green. If not, immediately power down the APDs and determine the cause of extreme light levels.
- (d) Check which APDs have their caps on, and read the counts measured for those particular APDs. Ensure that they coincide roughly with the dark count given by the datasheet.
- (e) Open and close the aperture iris on each fiber coupler and verify an observable change in the single counts on those channels.
- (f) Put apparatus in STANDBY mode and proceed to the next section.

Pulse Generator and Verifying Counts

Goal: Test LabVIEW singles counts with controlled inputs to the BNC HUB and verify that the singles count rate is equal to the frequency of generated pulses.

What you need to know:

In order to provide a controlled signal, a Pulse Generator (PG) has been provided which can produce 30 ns pulses at varying rates between 10 Hz and >10 MHz. For convenience, the amplitude of the PG has been preset to match that of the APD pulses. Try not to adjust either the coarse or fine amplitude adjustment knobs located above the + Output. Also, avoid changing the widths of the pulses, as these have been preset to the minimum of 30 ns.

Procedure:

- (a) Plug the pulse generator into a power outlet.
- (b) Disconnect all APD BNC cables from the BNC HUB.
- (c) Connect one BNC between the + Output of the PG and the A port of the BNC HUB. Ensure that the knobs are approximately in the position indicated by Figure 3.
- (d) Turn on the power to the PG. The power button for the PG is found at the bottom left of the front panel.
- (e) Click the "RUN" button in LabVIEW and observe the meter displaying the counts for the channel corresponding to the PG. Ignore the "APD Light Level" warning indicator for channels connected to the PG.
- (f) Try adjusting the repetition rate of the pulse generator either by adjusting the coarse or fine repetition rate knob. You should see the number of counts on the screen for that channel change accordingly.
- (g) To verify that the counts are actually what they are supposed to be, use the oscilloscope. Ensure that the oscilloscope is plugged in and turn it on.
- (h) Disconnect the BNC from HUB port A and connect the output from the PG to one of the inputs of the oscilloscope.
- (i) Adjust scales and trigger accordingly until a nice pulse can be seen on the screen. Check that the attenuation for the oscilloscope channel is 1x. You can do this by clicking the channel 1 or 2 button and using the prompts on the right hand side of the screen. Increase the horizontal scale until you can see multiple pulses spread over some time.
- (j) Read the frequency of these pulses either by measuring it on the oscilloscope or reading it

yourself. You can adjust the frequency of the PG to set the frequency to a convenient value, such as 100 000 Hz.

- (k) Disconnect the BNC from the oscilloscope and reconnect it to port A of the BNC HUB.
- (l) Run the LabVIEW program (if stopped) and read the number of counts on the channel. Note that if the update window is set to 1.0 s, the count is the actual frequency set on the PG.
- (m) Compare the frequency you read to that of what you found on the oscilloscope. Do they agree?
- (n) Place the apparatus in STANDBY mode and continue to the next experiment.



Figure 3 - Knob settings for pulse generator

Verify Coincidences

Goal: Test LabVIEW Coincidence counts using a controlled input to two, three and four BNC HUB ports and verify the detected coincidences equal the generated pulse rate.

What you need to know:

Now that we have the PG set up we can make sure that all of the types of coincidences work. To do this we will split the signal from the PG and input these signals into separate channels of the APD. Since they are the same signal, the pulses should be entirely coincident and thus the

number of raw coincidences should exactly match that of the counts. A note on using the T-splitters: to avoid spurious reflections attach the T's in the most symmetrical way possible and disconnect any unused cables.

Procedure:

- (a) Place the T-Splitter on the PG to split the output from the PG into two BNC cables.
- (b) Disconnect all BNC cables from the HUB and "RUN" the LabVIEW program.
- (c) Connect cables from the PG to every two-fold combination of A,B,C,D and verify that each meter shows the proper number of coincidences.
- (d) Connect additional T-Splitters to each side of the first T-Splitter in order to split the signal into 3 and 4 cables.
- (e) Connect combinations of cables to the HUB and verify that all 3-fold and the 4-fold coincidences are also working.

Note: Only the "Raw Coincidence" count is valid in this case since the pulses are generated in perfect coincidence. Ignore corrected values.

Verifying Pulse Shortening Mechanism

Goal: Probe the FPGA and verify that switches 17-13 on the DE2 board properly shorten the pulses roughly according to Table 1.

What you need to know:

The BNC HUB has been left open to allow for easy access to the pins of the 40 pin cable. Connected to the 40 pin cable are the four channel inputs A,B,C,D which are given by the green, blue, brown and purple wires. There is also a ground wire which is white. On top of these, many of the other pins are signals output from the FPGA for the purposes of debugging. These pins are shown in Figure 4.

Procedure:

- (a) Connect the voltage probes to both channels of the oscilloscope. Set the attenuation of each channel to 10x.
- (b) Connect the probes to the small red and yellow wires that have female pin connections on one end. Plug the female ends of these wires to the pins in the BNC HUB that correspond to A_original and A_shortened. The orientation is such that the top of Figure 4 is on the left side when looking into the BNC HUB. Double check the orientation by viewing the position of the already attached wires.
- (c) Ground the probes by attaching the alligator clips to the ground side of the resistors (same side at which white wire is attached to breadboard).
- (d) Connect the output from the pulse generator to port A of the BNC HUB.
- (e) Turn on everything except the APDs. Observe the pulses which should now appear on the oscilloscope. Trigger the oscilloscope to the probe attached to the A_original pin.
- (f) Adjust switches 17 through 13 on the DE2 board and observe the change in size and shape of the shortened pulse signal. Table 1 shows the approximate FWHM for each pulse according to the switch settings.
- (g) As a sanity check, try to measure the FWHM of one of the shortened pulses and compare to Table 1. Are they the same? It should be noted that the widths in Table 1 are an estimate, and to properly determine the widths you must perform a calibration as in the next experiment.
- (h) Note that for small pulses, the amplitude decreases. This is due to the rise time of the pulses and the fact that the oscilloscope has a limited bandwidth. This has a small impact

on the actual timing window created by the pulses, but is compensated for via calibration, to be done next.

- (i) Place the apparatus in STANDBY mode and continue to the next experiment.

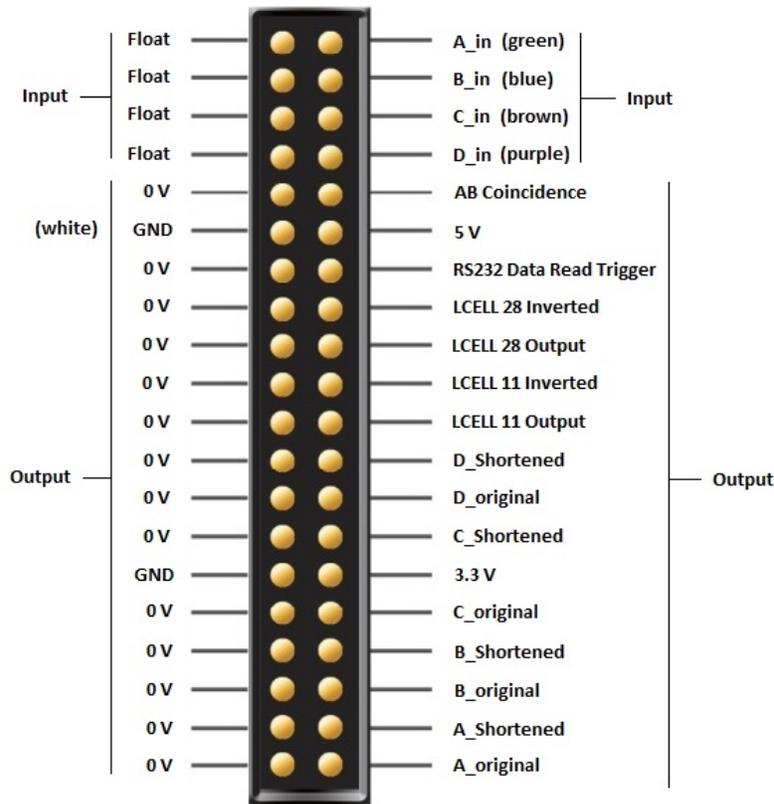


Figure 4 - Pinout diagram of 40 pin cable inside BNC HUB.

Verify Accidentals Correction and Measure the True Coincidence Window

Goal: Input random scattered classical light into the APDs at single counts of up to 200,000 c/s and verify that all coincidence counts are recorded as accidental coincidences.

What you need to know:

The LabVIEW program displays the raw counts read directly from the FPGA, as well as the expected statistical coincidences from background light. Ideally, since all of our testing involves “background” light, the corrected coincidences counts should be 0. However, this requires the user to have input the correct “effective” timing window (coincidence window). In order determine this “effective” timing window, we will check and calibrate our system.

Procedure:

- (a) Remove the probes from the previous experiment.
- (b) Reconfigure the apparatus such that the PG is connected to channel A of the BNC HUB (with no T-connectors on the PG), and a fiber coupled APD is connected to channel B.
- (c) Set the switches on the FPGA to any pulse width which you like, and enter the corresponding pulse width into the LabVIEW VI from Table 1 as a starting point.
- (d) Follow the ON Procedure with this configuration.

- (e) Observe that points appear in the LabVIEW plot. This is plotting the values of Eq. 1 versus the detected coincidence values on the x-axis.
- (f) Now adjust the rate of the PG and watch as the points on the plot move linearly. Again, ignore the warning light for the PG channel since you not using an APD.
- (g) After collecting a sample of data points, stop the LabVIEW program, turn off the APDs, and right click the plot to export the data to Excel.
- (h) The slope of the plot is the ratio between the $\tau_{LabVIEW}$ we supplied and the actual $\tau_{effective}$. This is because both the raw and expected statistical counts both following Equation 1 – with the exception that the expected statistical coincidence count uses $\tau_{LabVIEW}$. As such, the raw coincidences correspond to an actual $\tau_{effective}$.
- (i) Fit the data in Excel with a straight line. Using the slope and the τ you inputted, calculate the actual τ using Equation 1.
- (j) Now repeat this experiment, but this time enter $\tau_{effective}$ as the coincidence window value in LabVIEW. The line should have a slope of almost exactly 1. The corrected coincidences should now be centered about 0. You have now calibrated the coincidence window.
- (k) If you have time, try doing the same experiment with two APD's connected to channels A and B, and vary the amount of background light by adjusting the irises.