



FastGated SPAD Single-Photon Detection Module

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MICRO PHOTON DEVICES

FastGated SPAD Single-Photon Detection Module

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1 Getting Started

This chapter provides the introduction on the MPD FastGated Single-Photon Detection Module that will help you get acquainted with the product. It also includes the installation and configuration procedures that will support you in getting started with the system.

1.1 Introduction

The FastGated single-photon detection module is built around a Peltier cooled Silicon Single-Photon Avalanche Diode (SPAD), for the detection of UV, visible and NIR photons from 300 nm up to 1000 nm.

The module includes a programmable frequency and pulse generator for gating the detector, a front-end circuit for photodetector's avalanche sensing, a fast circuit for detector's avalanche current quenching and operative bias voltage resetting and others sub-circuits for signal conditioning. All the main parameters are adjustable by the user through a software interface, in order to match the requirements of the different applications.

The system is composed by two parts:

- A Detection Head, which comprises a Silicon SPAD detector and the related fast electronics. Its small dimension allows its easy integration in all experimental setups.
- A Control Unit, which contains the pulse generator, the Peltier controller, the communication system and the power supplies of the entire module.

They are connected together through a 2 m long wide-bandwidth cable.

The system can be conveniently used both for counting and timing measurements, since the high-performance electronics guarantees a clean temporal response even with fast gate transitions.



Figure 1. The FastGated single-photon detection module.

1.2 The Photon Detection Module

1.2.1 Standard module configuration

A standard FastGated single-photon detection module is usually shipped with these parts:

- Control Unit;
- Detection Head;
- Orange wide-bandwidth Cable for Control Unit to Detection Head connection;
- MPD universal optical table adaptor for Detection Head mounting;
- Power cord;
- USB key containing the installation software and this user manual in PDF format;
- A SPAD test report.

1.2.2 Preparation for use and care.

Before using and powering-on the module the following precautions must be followed:

1. The FastGated SPAD **must** be unpacked and set-up as reported in paragraph 3.1.1.
2. Connect and disconnect the orange wide-bandwidth cable **only** when the module is powered off. Avoid switching on the module if the orange wide-bandwidth cable has not been properly connected to both the Control Unit and the Detection Head.

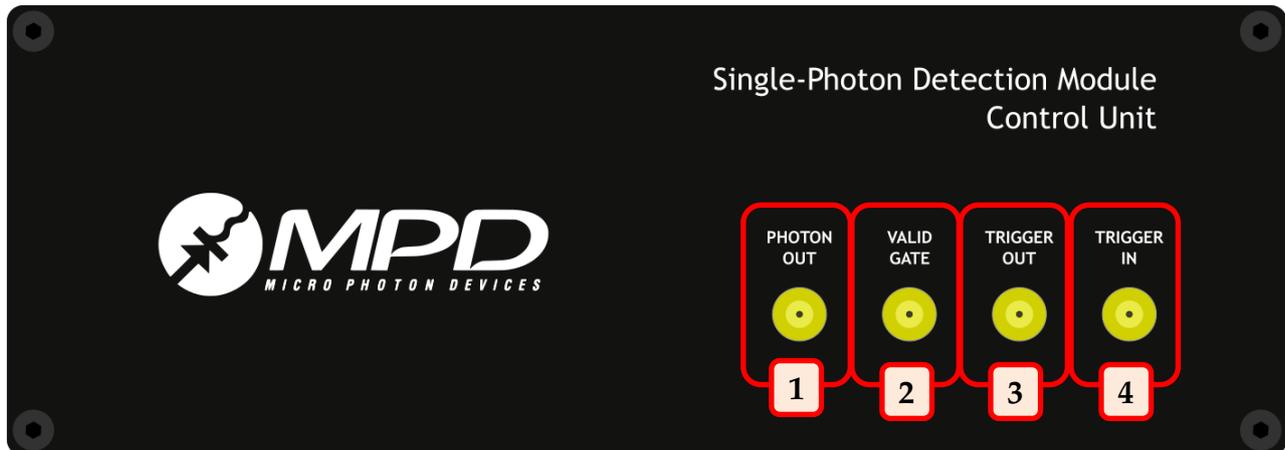
3. In order to use the module, the controller software has to be installed on a PC, following the instructions in paragraph 2.1.
4. **Never** switch-off the module if the SPAD has not being turned off by the control software as explained in paragraph 3.1.4.
5. Before connecting any cable to the front panel connectors, make sure that signals are compatible with the levels specified in Chapter 4. Also pay attention on signals polarity and invert them if necessary.

1.2.3 Care of the SPAD optical interfaces

Please follow these instructions for cleaning the input optical window of your detection head:

1. Dust and other loose contaminants usually should be blown off before any other cleaning technique is employed. A canister of inert dusting gas or a blower bulb is suggested for this procedure. Do not use your mouth to blow on the surface because it is likely that droplets of saliva will be deposited on the optical surface.
2. If this is not sufficient, other cleaning methods for optical surfaces are acceptable. Always use clean wipes and optical grade solvents to prevent damage from contaminants. Wipes should always be moist with an acceptable solvent and never used dry. Acceptable wipes are pure cotton, lens tissue;
3. Typical solvents employed during cleaning are distilled water and isopropyl alcohol. Use all solvents with caution since most are poisonous, flammable, or both. Read product data sheets and MSDS sheets carefully before using any solvents;
4. If repeated cleaning is required, the use of distilled water it is recommended. Apply the smallest amount of pressure when wiping the surface with lens tissue paper.

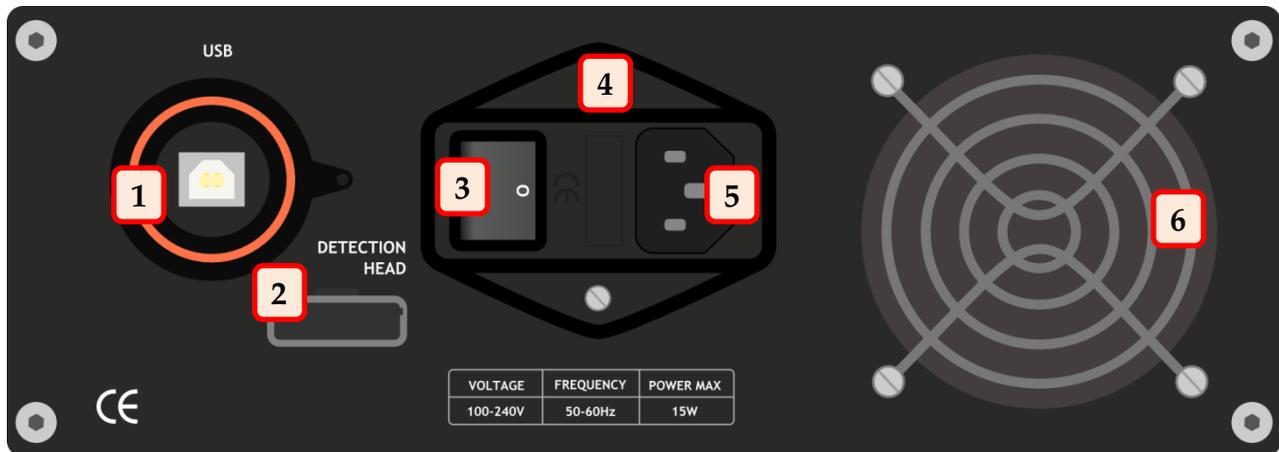
1.3 The Control Unit's Front Panel



1. PHOTON OUT : *output*, SMA connector;
a digital pulse is generated for each detected photon; the output is a NIM pulse, which means that it must be 50 Ω terminated and that the low logic level is 0 V and the high logic level is -800 mV. The falling edge of the pulse marks, with very low jitter, the photon arrival time;
2. VALID GATE : *output*, SMA connector;
outputs which *Gate* pulses effectively enabled the SPAD (non-masked gate pulses). The pulses are LVTTTL standard. See paragraph 1.5 for a detailed description of the VALID GATE signal;
3. TRIGGER OUT : *output*, SMA connector;
outputs the internal trigger reference signal used to periodically enable the SPAD. Normally disabled, it is enabled only when *internal trigger* is selected from the user interface. The pulses are LVTTTL standard;
4. TRIGGER IN : *input*, SMA connector;
if an external trigger is needed, then the signal must be connected to this input. The external trigger signal can be positive or negative within the range from -2 V to +2.5 V and the internal comparator allows for a programmable threshold.

For a complete understanding of the module input and outputs and their absolute maximum ratings please refer to Chapter 4.

1.4 The Control Unit's Rear Panel



1. USB Connector : holds the USB type-B cable for PC connection;
2. Detection Head cable connector : holds the wide-bandwidth cable for Detection Head and Control Unit connection;
3. Power Switch : used to switch on and off the module;
4. Fuse Holder : contains the 1 A fuse, to protect this appliance;
5. Power Inlet : holds the power cord to supply the unit;
6. Fan opening : permits the air to recirculate into the unit.

1.5 The FastGated Single-Photon Avalanche Diode

The core of this module is a Single-Photon Avalanche Diode (SPAD), housed into the Detection Head. The detector has a 50 μm diameter active area and it is mounted on the top of a two-stage Peltier cooler. A SPAD is a p-n junction, biased well above the breakdown voltage (V_B) that stays in a meta-stable state with no current flowing. At this bias, the electric field is so high that a single charge carrier injected in the depletion layer can trigger a self-sustaining avalanche [1]. The current rises swiftly (nanoseconds or sub nanosecond rise-time) to a macroscopic steady level, in the milliampere range. If the primary carrier is photo-generated, the leading edge of the avalanche pulse marks the photon arrival time. The current continues to flow until the avalanche is quenched by lowering the bias voltage down to or below V_B . Then the bias voltage must be restored, in order to detect another photon. These operations are usually performed by a suitable circuit, named Active Quenching Circuit (AQC) [2].

The device primary source of internal noise consists in a random dark-counting rate (DCR) arising from free carriers thermally generated. These events compete with photons in triggering the detector and thus impair the signal to noise ratio [1]. The Peltier cooler can be used to lower the temperature of the detector, diminishing this effect, or to simply keep the temperature constant, to have DCR stable in time.

Normally single-photon detectors are operated in the so-called free-running mode, where the devices are enabled immediately after the quenching of each avalanche current. The FastGated SPAD can also be usefully operated in gated regime: the detector is periodically enabled for a short time window called *Gate*, of duration T_{ON} (*Gate Width*), whereas it is usually held off at a bias slightly below the breakdown voltage.

The count rate (CR) of a detector operated in free running, and not in gated mode, is simply the number of counts generated by the module output (PHOTON OUT) divided by the integration time:

$$CR = \frac{\text{Number of Counts}}{\text{Integration Time}}$$

When the detector is operated in gated mode, the CR must be corrected taking into account both the *Gate Frequency*, i.e. the frequency at which the SPAD is periodically enabled, and the *Gate Width* (T_{ON}), i.e. the time length during which the SPAD is turned on during each duty cycle. The correction is due to the fact that photons (or dark-counts) may be absorbed during the times the SPAD is kept turned off and so are not counted. The correction takes into account how many photons have been counted and for how long, during the integration time, the SPAD has been kept really turned on. In order to calculate the true counting rate, the following formula must be used:

$$CR_{DUTY} = -\frac{1}{T_{ON}} \log (1 - CR \cdot T)$$

where T is the *Gate Period*, i.e. the reciprocal of the *Gate Frequency*. In most of the applications, this formula can usually be approximated to:

$$CR_{DUTY} \cong CR \cdot \frac{T}{T_{ON}} \quad \text{for} \quad CR \cdot T \ll 1$$

that is the raw counts divided by the duty-cycle applied to the detector.

However, a secondary source of noise exists in SPADs: the afterpulsing. During the avalanche some carriers are captured by deep levels in the junction depletion layer and subsequently released with a statistically fluctuating delay. Released carriers can retrigger the avalanche, generating after-pulses correlated with a previous avalanche pulse which sum up with the DCR. In order to mitigate these avalanche re-triggerings, after each avalanche, the detector is kept off for a user programmable time, named hold-off time, T_{HO} . In this way, the trapped carriers can be released without triggering further avalanches. An example of how a photon counter module operated in gated mode and employing the hold-off feature works is shown in Figure 2. The reference signal is the *Gate Sync* which sets the gate repetition rate (frequency) and whose ON time corresponds to the T_{ON} of the SPAD. The *Gate* instead is the actual signal applied to the SPAD. Initially the *Gate* and the *Gate Sync* are the same. When a photon is absorbed, it triggers the avalanche current, which is marked in this example by the raising edge of Photon Output pulse. Once the avalanche is detected it is immediately quenched; the system does not wait for the end of the Gate window to bias below breakdown the SPAD. Now *Gate* and *Gate Sync* begin to differ. Let suppose for sake of clarity that the hold off time is long about $2T$ (twice the gate period): during the hold-off time, the *Gate Sync* pulses are ignored, and the *Gate* remains low, keeping the photodetector OFF. The SPAD is enabled again only at the first rising edge of the *Gate Sync* signal after the end of the hold-off. The FastGated Module, in fact, allows to keep the detector OFF during a T_{ON} started before the end of the hold-off, so that the user does not risk losing useful information contained in the first part of the ON periods.

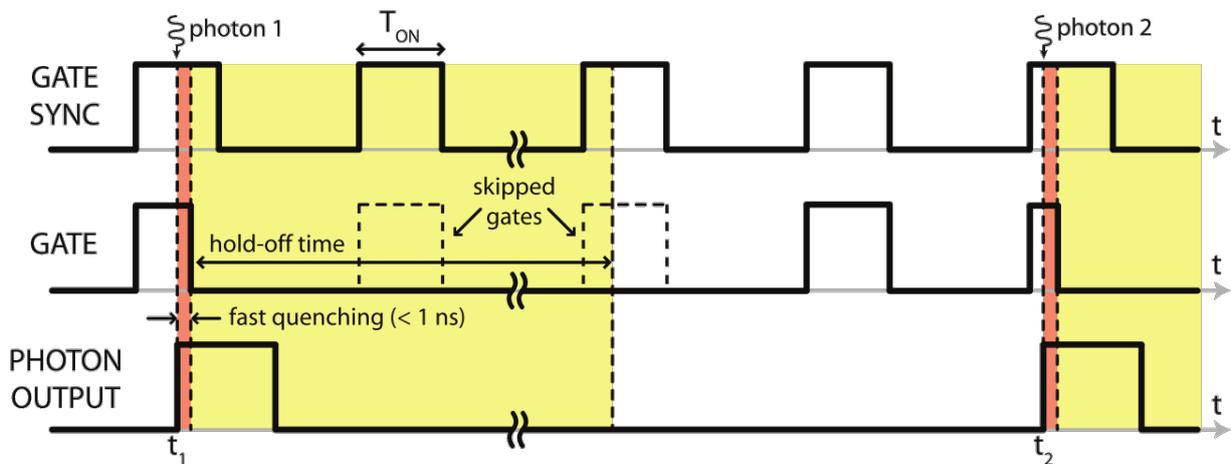


Figure 2. Main waveform in the module: output of pulse generator (GATE SYNC), pulses at the SPAD detector (GATE) and photon output signal (PHOTON OUTPUT).

Now, because of the hold-off time, the measured counting rate CR is not equivalent to the actual rate of photons but can be estimated by:

$$CR_{HO} = \frac{CR}{1 - CR \cdot T_{HO}}$$

In counting applications, the maximum count rate should be then limited at about $1/(2T_{HO})$, because for higher values the correction factor becomes so high that even small errors in the equation's parameters will result in high errors in the CR_{HO} counting-rate.

Since the MPD FastGated single-photon counter biases the SPAD in gated mode and applies the hold-off every time an avalanche is detected, the two described corrections must be applied at the same time in order to obtain the right photon counting rate CR_{photon} from the measured counting rate CR. From simple mathematics, it turns out that the final equation is the following:

$$CR_{photon} = -\frac{1}{T_{ON}} \log \left(1 - \frac{CR}{1 - CR \cdot T_{HO}} \cdot T \right)$$

which can then be simplified to:

$$CR_{photon} \cong \frac{CR}{1 - CR \cdot T_{HO}} \cdot \frac{T}{T_{ON}} \quad \text{for} \quad \frac{CR \cdot T}{1 - CR \cdot T_{HO}} \ll 1$$

Please note that the previous equations do not take into account the Photon Detection Efficiency of the SPAD. Also, these formulas strictly apply when the photon rate is uniformly distributed over time. Particular care must be used when applied to specific cases like the one discussed in paragraph 3.2.2.

Figure 2 is, in addition, very helpful in explaining the VALID GATE output. This signal is generated in order to properly trace which *Gate Sync* pulse effectively enabled the SPAD, i.e., which are the pulses that were not blanked during the hold-off time (VALID GATE has the same pattern of Gate, shown in Figure 2). This information is particularly useful when looking for the percentage of counts over the total number of available valid gates. In fact, in timing measurements one must be careful not to exceed the single-photon statistics, in order not to distort the TCSPC histogram (see paragraph 3.2.2).

1.6 Bibliography

- [1] Cova, S., Ghioni, M., Lacaita, A. L., Samori, C., and Zappa, F. "Avalanche photodiodes and quenching circuits for single-photon detection", *Applied Optics*, 35(12), 1956–1976 (1996). <http://dx.doi.org/10.1364/AO.35.001956>
- [2] Cova, S., Ghioni, M., Zappa, F., Rech, I., and Gulinatti, A., "A view on progress of silicon single-photon avalanche diodes and quenching circuits", *Proceedings of SPIE*, 6372, pp. 63720I-1 - 63720I-12 (2006). <http://dx.doi.org/10.1117/12.685963>

2 The Control Software

This is the operator's reference chapter, which contains information on the software user interface of the FastGated Single-Photon Detection Module.

2.1 Software Installation and Startup

Complete the following steps to install the Windows® controlling software. Note: in order to properly install the drivers during the first system startup, the computer **must be connected** to the internet.

- Log in as system administrator or as a user with administration privileges.
- Disable any automatic virus detection programs before you install. Some virus detection programs could interfere with installation.
- Insert the USB key and copy the Install_for_Windows folder in a temporary location (for example your Desktop).
- Double click on the file named setup.exe, located inside the folder you just copied.
- Follow the instructions on the screen until the installer ends.
- After having connected the FastGated system with the procedure detailed in Chapter 3.1.1, connect the USB cable to the PC, and turn on the module.
- Windows® will automatically recognize the device and install the correct drivers. If a “found new hardware” window appears, select the option to automatically download recommended drivers from internet. The drivers will create a virtual serial COM associated with the FastGated single-photon counter.
- Once completed, start the controlling software from Windows Start Menu → Programs → MPD → FastGated Single Photon Detection Module.
- Remove the temporary install folder.

2.2 Start Tab

When the software is started for the first time, the window illustrated in Figure 3 is shown. The window has two tabs: *Start* tab and *Summary*, as well as a menu bar.

With the *Start* tab, it is possible to detect and name all the FastGated SPAD modules connected to the PC where the controlling software runs. *Detected Modules* table and buttons *Autodetect* and *Accept Config* are available on this tab.

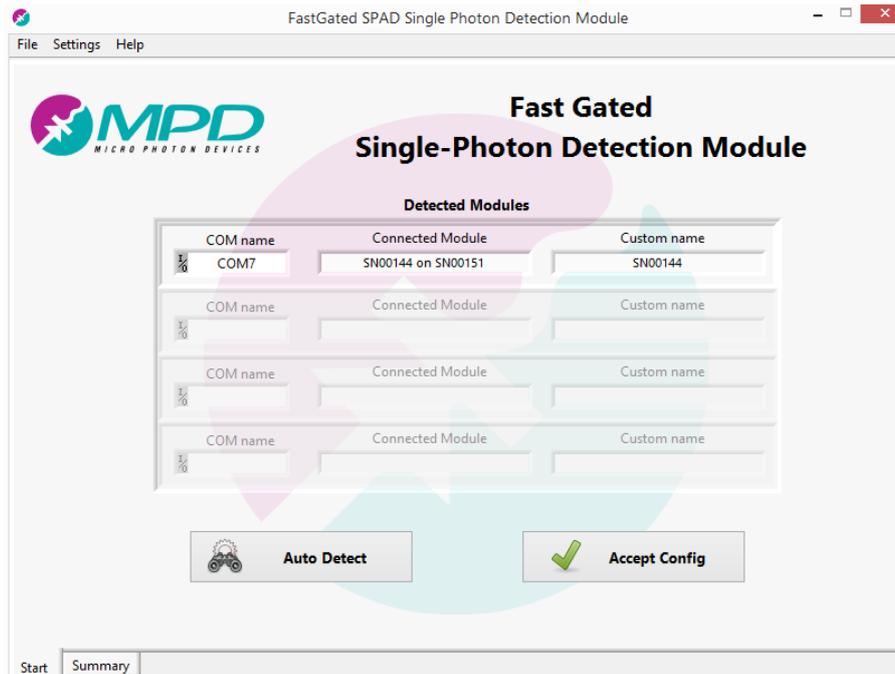


Figure 3. Start tab screenshot with one detected module.

2.2.1 Detected Modules table

In this table are reported all the detected modules. For each one, the software displays the Detection Head and Control Unit Serial Numbers and, in order to simplify the identification in the user setup, a custom name can be assigned. This is linked to the Detection Head and saved to disk, so it is recalled every time the specific Detection Head is employed. This is true even if the Detection Head is connected through a different Control Unit. Any name can be chosen as Custom Name. By default, the Custom Name corresponds to the Detection Head's serial number.

If the software has detected all the connected modules and the user has associated all the custom names, the *Accept Config* button can be clicked. By accepting the configuration, the software will create additional tabs, one for each detected module as shown in Figure 4.

Each tab will allow the user the full control of the associated photon counter as will be shown in paragraph 2.4.

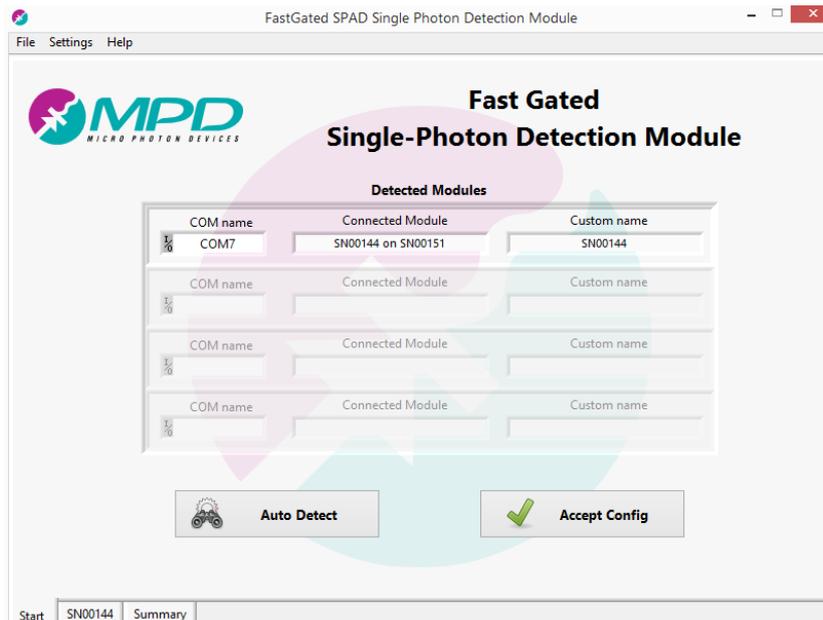


Figure 4. Start Tab screenshot after module renaming and “Accept Config” button pressed.

This table is automatically populated at each software startup with actual connected modules, unless the user has disabled the automatically search feature in the options panel, as will be explained in paragraph 2.3. If other modules are connected to the PC afterwards, it is necessary to manually press the *Auto Detect* button as explained in the following section.

2.2.2 Auto Detect button

Pushing this button, the software scans each COM port available on the system and sees if there is any attached module; then the *Detected Modules* table is updated according to the current scan. This function is automatically run when the program starts, unless a static COM number is assigned in the *Settings->Options* configuration window, shown in Figure 5.

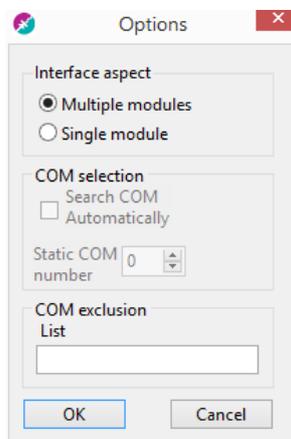


Figure 5. Options configuration window.

2.2.3 Accept Config button

By pressing this button, the custom names, that have been assigned to the connected modules, are confirmed and the program populates the tabs with one page for each recognized system. Tabs report the *Custom Name* that has been given to each module.

2.3 Menu Bar

The menu bar has three menus: *File*, *Settings* and *Help*. The *File* menu has only one item Exit and is used to exit immediately the program when all the SPADs are off.

Options configuration window (shown in Figure 5) is activated though menu Settings → Options. Please note that you have to restart the program in order to make any change, in this window, operational. Inside *Options* window there are the following controls:

- *Interface aspect* radio button: it lets you to switch between *multiple* or *single module interface*. Using this last option, tabs are not shown and only one module can be managed. This option is useful when the user employs only one photon counter.
- *Search COM automatically* checkbox: in *Multiple modules* interface mode always enabled. This option can be set as desired only if the software has been set in *Single module* interface mode. If disabled, it does not force the program, during the start-up, to find automatically the right COM port where a module is connected. This option is very useful when the PC handles other serial instruments.
- *Static COM number* control: when the auto-detect checkbox is disabled, the COM port, to which the photon counter has been connected, must be specified in this field.
- *COM Exclusion List*: it lists the COM port numbers that have to be excluded from the automatic detection process. Use comma as number separator. This option is useful when other serial instruments are connected to the PC; if in the list, they will not receive the command CS#, which is sent by the software to identify connected modules.

By pressing *Help*, on the menu bar, the menu shown in Figure 6 will appear.

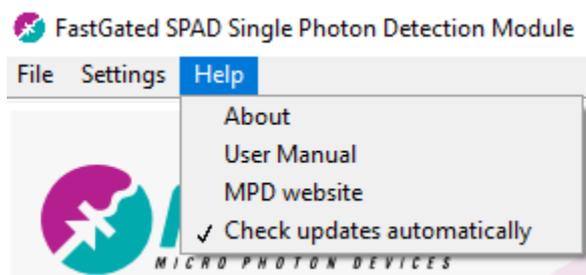


Figure 6. Help menu.

The *Help* menu lists the following items:

- *About*: when pressed a dialog box showing the program name, version and copyright will appear.
- *MPD website*: when pressed, the default web browser will open on the MPD webpage.
- *User Manual*: when pressed the default PDF reader will be opened and the FastGated user manual will be shown.
- *Check Updates automatically*: when this item is ticked, on start-up, the FastGated SPAD control software will look for software or user manual updates on the MPD website.
 - In case a new user manual is present, the dialog box shown in Figure 7 on the right will appear and if the user presses the ‘Yes’ button the new user manual is downloaded and copied inside the program. A dialog box signaling the successful install of the new manual will also be shown as illustrated in Figure 8.
 - In case a new software is available, the dialog box shown in Figure 7 on the left will appear. If the ‘Yes’ button is pressed, the default web browser will be opened directly on the download page of the MPD website.

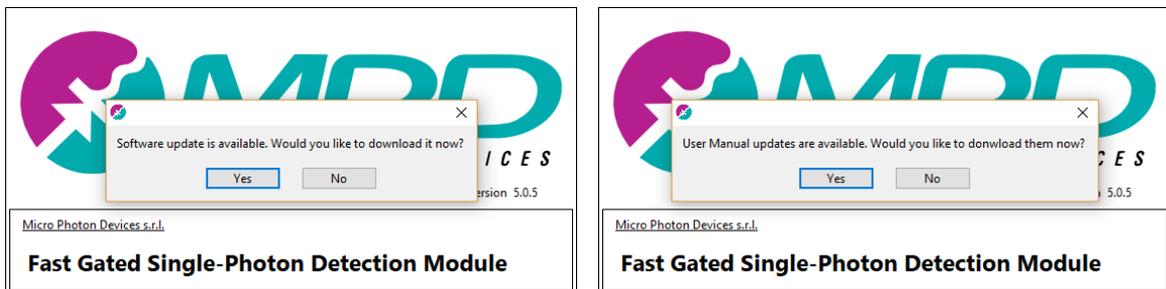


Figure 7. Software Update (left) and User Manual update (right) dialog boxes.

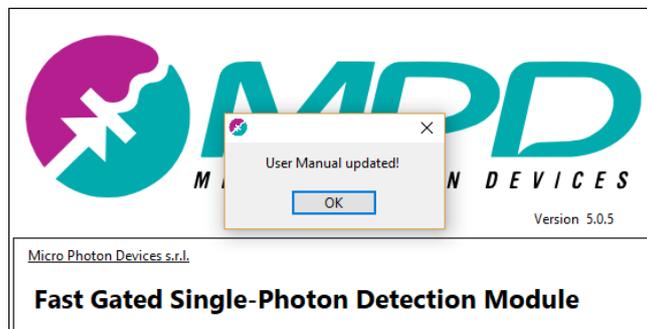


Figure 8. Dialog box informing that the User-Manual has been downloaded.

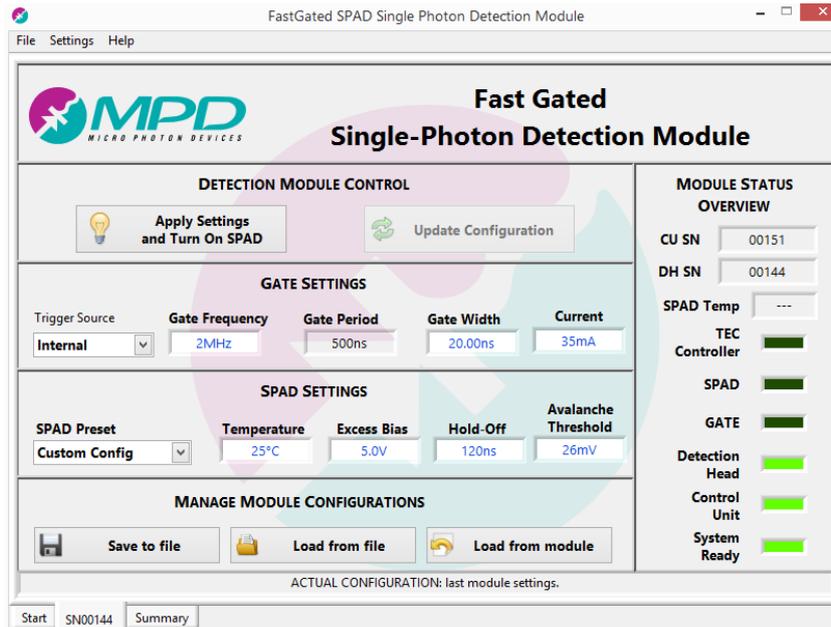


Figure 9. Module tab screenshot before turning on the SPAD.

2.4 Module Tab

After clicking the *Accept Config* button in the *Start* tab, the software creates a module tab for each attached system. The tab label reflects the *Custom Name* given at the specific module. Every module tab opens an interface whereby all the configurable parameters of the detector, the trigger and the gate signals, can be set. A working configuration, even though not optimized for the particular user application, can be loaded through the SPAD Preset drop-list menu (*working-config*). Otherwise the user can change all the available parameters, using the *custom-config*. In Figure 9 it is reported a page screenshot, taken before turning on the SPAD. The next paragraphs will describe all the controls, buttons and indicators that can be found into this window, divided by section.

2.4.1 Detection Module Control

In this section of the panel there are two buttons: *Apply Settings and Turn On SPAD* and *Update Configuration* (Figure 9). The first button changes to *Turn Off the SPAD* after the FastGated SPAD has been turned on, as shown in Figure 10, and will revert to the initial name after the turn off procedure. The two buttons are used to upload the user-defined parameters in the control unit and turn on and off the detector; in particular:

- *Apply Settings and Turn On SPAD* button: if the detector is off, you can configure SPAD parameters (i.e. the operating temperature, excess bias, hold-off of the photodetector and the avalanche-detection threshold) and set the trigger and the gate parameters as described in next paragraphs. Completed this task, by pressing this button, all the settings are sent to the module and the detector turns on.

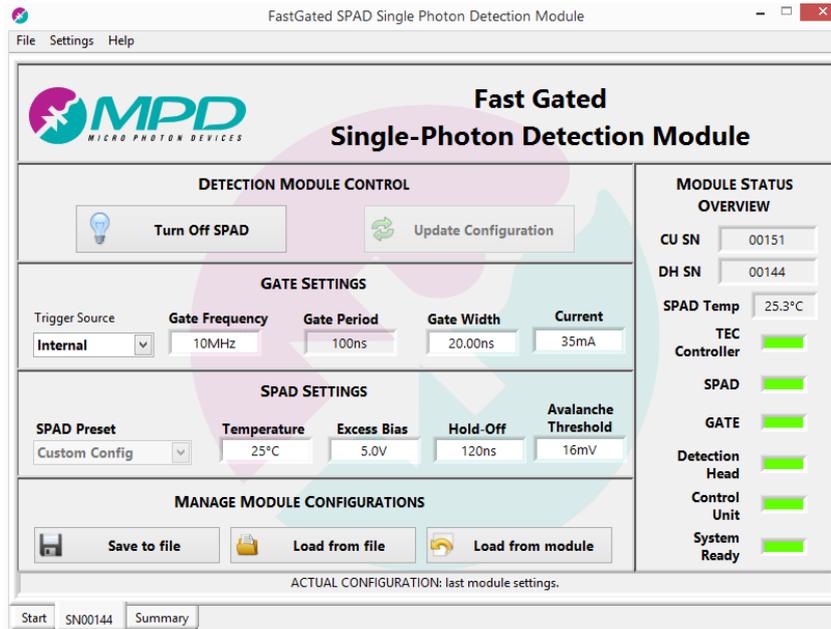


Figure 10. Module tab screenshot after having turned on the SPAD.

- *Update Configuration* button: once the SPAD is on, trigger and gate parameters can be changed at user convenience. The modified values are then uploaded immediately in the module by pressing this button. Note that this button becomes active only when at least one parameter is changed since the last update. The values which have been changed, but not yet uploaded, are highlighted in blue as shown in Figure 9. A change of some of the settings may require a detector power off and a consequent power on transient, but this is carried out automatically by the module.
- *Turn Off SPAD* button: if the SPAD is on, this button replaces the *Apply Settings and Turn On SPAD* one. In order to shut down the detector, this button must be clicked, and the user has to wait until the *SPAD* status LED, in the *Module Status Overview*, is off. Please note that the *Turn Off SPAD* button must be pressed and the *SPAD* status LED must have become off, before switching off the complete module by using the power switch located on the module rear panel. If this procedure is not followed, the *SPAD* detector may be damaged.

2.4.2 Gate Settings

In the *Gate Settings* section, the parameters related to the gated-mode operation of this module can be set. The photodetector is only enabled for a programmable time, named *Gate Width* (T_{ON}), every time a trigger event occurs, as described in paragraph 1.5. This trigger can be externally sent to the module by the TRIGGER IN input or internally generated by the module. The *Gate Width* instead is always produced with the internal circuitry. In addition, the module can be operated in free running mode. The working modality is selectable through the *Trigger Source* drop box list, shown in Figure 11.

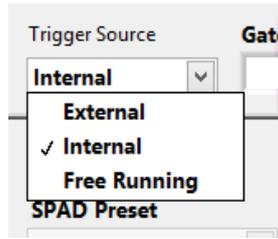


Figure 11. Trigger selection drop menu.

The following section details the available controls allowed by the user interface:

- Free-running:

The module can be used as a normal free-running module where the SPAD is immediately enabled following an avalanche detection and the associated hold-off. With this setting, as shown in Figure 12, no other gate settings are visible since in this modality there is of course no synchronous triggering and the *Current* setting (present in the *Gate Settings* section and discussed later in this paragraph) has been set to an optimal value.

- Internal Trigger - Gated Mode:

The module can work also in gated mode, since, inside the FastGated SPAD Module, there is a programmable trigger reference, that could be used to periodically enable the detector and trigger external instrumentation through the TRIGGER OUT output connector. This section is built around a high-performance Phase Locked Loop, with a crystal quartz reference, which guarantees a low jitter output and a highly frequency customization. When this modality is selected, the controls shown in Figure 13 get active. Through the *Gate Frequency* control, the user can specify the trigger frequency in Hertz; the *Gate Period* indicator shows in real time the inverse of the set trigger frequency. The allowable trigger frequencies are reported in Table 1 as well as in Chapter 4 for reference.

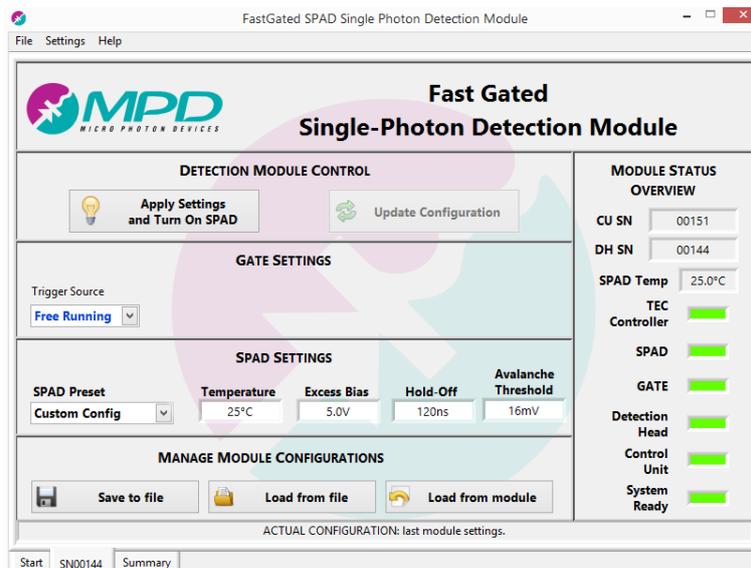


Figure 12. Module tab screenshot after having selected the Free Running mode.

Table 1. Internally available Gate Frequencies.

Frequency range	Allowable frequency
200 Hz ÷ 1 MHz	1 – 2 – 4 – 5 – 8 steps
1 MHz ÷ 25 MHz	100 kHz steps
25 MHz ÷ 80 MHz	1 MHz steps

It is important to notice that, in order to confirm frequency modifications and upload them to the module, the *Update Configuration* button shown in Figure 10 must be always pressed.

- External Trigger – Gated Mode:

The module could also be triggered by an external reference signal, provided by the user. This is typically derived from the laser sync output. By selecting the *External source* with the menu in Figure 11 the panel shown in Figure 10 and highlighted in Figure 14 will appear. With the controls in this panel, both the valid edge and the input threshold voltage can be chosen. In this way, many different logic levels can be accepted by TRIGGER IN input. See Chapter 4, for the electrical specifications.

- Gate Width:

The duration of the enable pulse of the SPAD detector can be set in a range of values that span over more than three decades. In particular, there are two different ranges: one from 2 ns to 10 ns, with a programmable step of 40 ps and a second one from 10 ns up to 500 ns, with steps of 2 ns. The selection of the range is automatically chosen by the program, according to the value inserted in the *Gate Width* control, shown in Figure 15.



Figure 13. Internal Trigger configuration control and indicator.



Figure 14. External Trigger configuration controls.

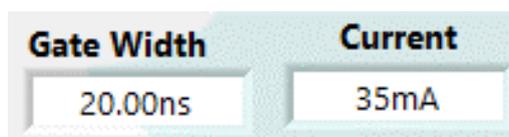


Figure 15. Gate width and Current controls.

If the *Internal Trigger* mode has been selected, the inserted value in the *Gate Width*, plus a minimum gate-off time (see paragraph 4.5) for the detector, cannot exceed the *Gate Period*; the MPD software will automatically check if this condition is met, giving a warning message in case it is not. Instead, when the *External Trigger* mode is selected, the respect of this requirement must be ensured by the user. A failure to respect this requirement might shut off the Detection Head, with the appearance of a dialog message signaling the error. For example, if the *Gate Frequency* is 80 MHz, the *Gate Period* is about 12.5 ns and thus the *Gate Width* cannot be more than 7.5 ns.

Entering the value of 0 ps as *Gate Width* lets you to disable the detector, without pressing the “Turn Off SPAD” SPAD. In order to re-enable it, a non-zero value must be inserted.

- Current:

This parameter (see Figure 15) allows the user to control and adjust the swiftness of the gate rising edge, after having set all the other gate parameters. A high current allows for faster rising times but might introduce wider ringing in the optical gate shape, especially on the flat part and close to the rising edge. A low current allows for a smoother gate shape with only minor ringing, but a slower rising edge. A value of 35 mA is a good value to start any test aimed at finding the optimal current setting.

It is also worth noting that for all the user selectable settings (Gate Settings and the SPAD settings described in the following paragraph), all user input settings are verified by the SW and any value outside its limits, will be automatically forced to the nearest allowed maximum or minimum value.

2.4.3 SPAD Settings

With the panel shown in Figure 16, you can select detector Temperature, Excess Bias, Hold-off and Avalanche Threshold. All parameters are self-explaining with the exclusion of Avalanche Threshold. This controls the threshold of the fast comparator used to sense the onset of the SPAD avalanche current: a low value allows for best timing performance but might cause the comparator to be triggered even by noise; a high value allows for noise immunity with a larger jitter and decreased sensitivity as the avalanches can be triggered close to the gate edges.

It is highly suggested to optimize this together with the current parameter once all the other operating settings (in particular excess bias, trigger frequency and gate-on time) have been found for the specific measurement, and with the module properly warmed-up. Increase the current value from the suggested one of 35 mA until the edges of the gate window are fast enough for the specific application or until the oscillations (seen on the flat part of the gate window) are tolerable. Then start to decrease the Avalanche Threshold parameter until narrow spikes start to appear at the rising or closing edges of the gate. The optimal value is 2 – 4 mV higher than this value. The suggested starting value for this Avalanche Threshold optimization is 16 mV. In some cases, once triggered, the spikes on the edges may not disappear even if the Avalanche Threshold is set to the found optimal value. In this case it is suggested to set the

parameter to a value higher than 30 mV, update the settings, and then set again the previously found optimal value.

In case of free-running operation mode, the described optimization procedure cannot be used. In this case, it is suggested to decrease the Avalanche Threshold voltage, from the suggested starting point of 16 mV, while keeping the output count-rate precisely monitored, and stop as soon as a count-rate increase is detected. Use a proper integration time to minimize the Poisson noise influence. Once again, increase the found value by 2 – 4 mV for the optimal one.

Through the *SPAD Preset* drop-box list it is possible to select a SPAD configuration, which is a particular combination of all the available parameters. The user can choose between: i) a working configuration, which cannot be changed, and allows to set the module with a good trade-off between all parameters; ii) a custom configuration, which allows to selectively change and optimize each parameter, since all the parameters are unlocked.

SPAD Preset selection can be changed only when the detector is off. Thus, you have to use the “Turn Off SPAD” button if the diode is active. Modifications are applied at the next start of the detector, that is using the “Apply Settings and Turn On SPAD” button.

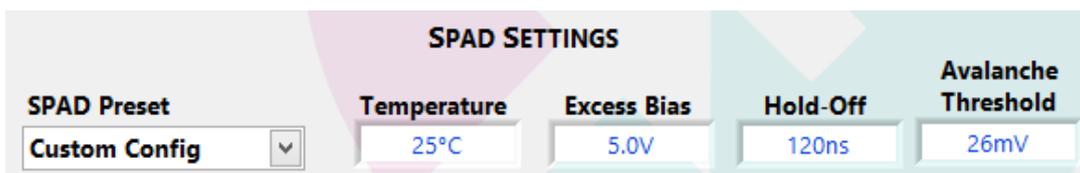


Figure 16. Advanced SPAD configuration, with fancy values.

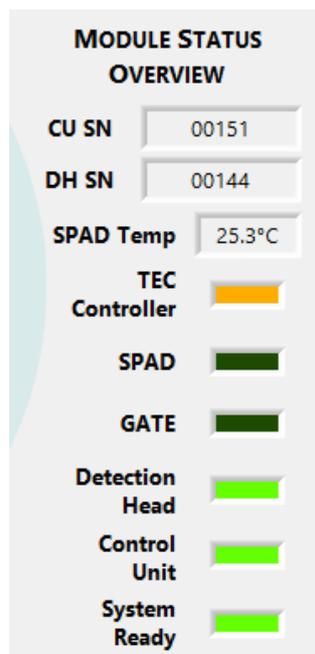


Figure 17. Module Status Overview indicators, during detector power on.

2.4.4 Module Status Overview

In this panel, shown for example in Figure 10 and depicted in Figure 17, there are six status LEDs, and three other indicators. The LEDs color description are:

- *TEC Controller* LED: it turns yellow to indicate that the thermoelectric cooler has been powered on and the temperature is going to reach the desired steady state value. When the device reaches the right value, the LED becomes green. It is off while the TEC is inactive. It turns red if the desired temperature cannot be reached.
- *SPAD* LED: it turns yellow to indicate the transient of the SPAD bias voltage to the correct value just below breakdown and green to point out the steady state of this one. When the bias is inactive, this LED is off. It turns red if the correct bias voltage cannot be reached.
- *GATE* LED: it turns green when the gate signal is applied to the detector; it is inactive when the gate is off.
- *Detection Head* LED: it turns red when there is no communication with the Detection Head or when the maximum Gate Width is not satisfied (external trigger). Otherwise, it is green.
- *Control Unit* LED: it turns red only when there is no communication with the Control Unit. Otherwise, it is green.
- *System Ready* LED: during the normal functioning of the whole system it is green; it turns red only when an error inside the module is detected.

Other indicators in this section are:

- *CU SN*: MPD serial number of the connected Control Unit.
- *DH SN*: MPD serial number of the connected Detection Head.
- *SPAD Temp*: the current temperature of the detector in Celsius degrees. It is active only when the TEC controller is active; in all the other cases it does not show anything.

There is also a status bar at the bottom of the module window (shown for example in Figure 12): it reports the module loaded configuration or error messages.

2.4.5 Manage Module Configurations

The FastGated SPAD Module automatically saves and recall at startup the last settings used which are displayed in blue ready to be uploaded again in the module. Anyway, sometimes it is more convenient to save different configurations for different setups. For this purpose, you can use the *Save to File* or the *Load from File* buttons, shown in all the module tab pictures and highlighted in Figure 18. If one of these buttons is pressed, a standard save-or-load window appears and it is possible to create, overwrite or open an existing file in the preferred directory.



Figure 18. Manage Module Configurations buttons.

All user data, including SPAD settings, Gate Width, Current and the Trigger setup are stored in a user-named binary file any time the *Save to File* button is pressed. Use *Load from file* to recall saved settings to the user interface. All previous settings will be lost. Use *Update Configuration* or *Apply Settings and Turn On SPAD* buttons to upload these new settings to the module.

Load from module button is used to recall and display the parameters currently set on the module. It is suggested to use this button after every *Update Configuration*, in order to be sure that the displayed parameters match the ones on the module. Even in this case, all the previous displayed data will be overwritten.

2.4.6 Error control

In case of errors the module tab will be framed in a red rectangle as shown in Figure 19. The module tab name will also turn red. A red LED in the *Module Status Overview* will mark the error type. Please refer to paragraphs 2.4.4 and 3.5 for a correct understanding of the various possible errors and for troubleshooting. In case of a communication error see immediately paragraph 3.5 before powering-off the module. In case of all the other errors the module turns off the SPAD and does not accept any more commands, thus it is necessary to switch off the module. Before switching it on and detecting it again, it is advisable to solve the cause of the error.

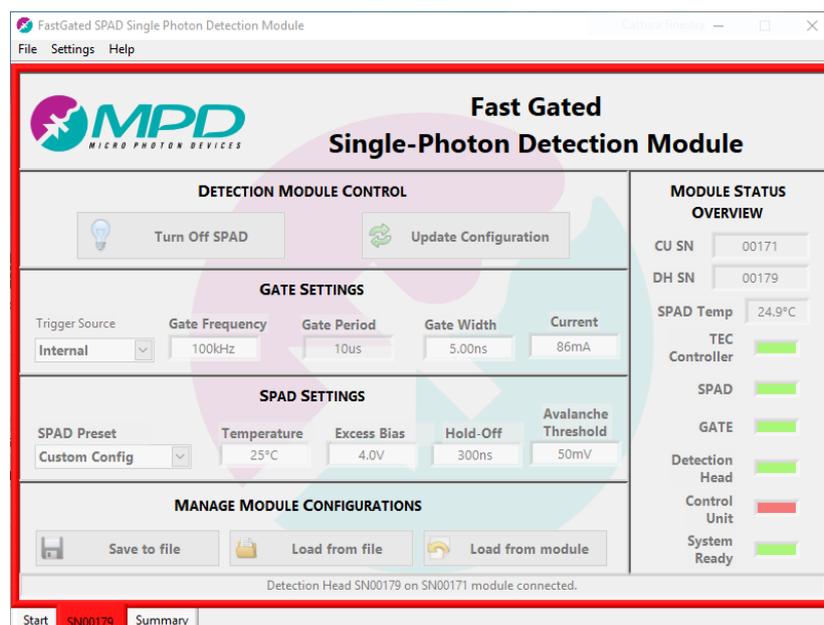


Figure 19. Screenshot of a Module tab when an error is detected.

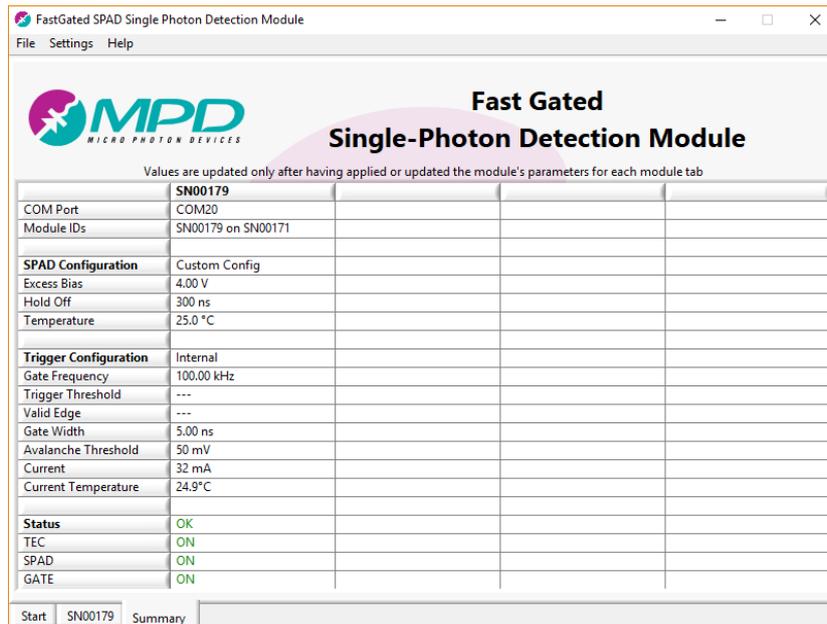


Figure 20. Summary tab showing a connected module.

2.5 The Summary Tab

The Summary tab (see Figure 20) illustrates all parameters that have been set for each currently connected module, in a single screenshot; furthermore, it reports the status of every device. Since a maximum of four FastGated Single-Photon Detection Modules can be connected to a single PC, there are four columns that are filled with the appropriate parameter/status, indicated by the row header.

This screen is only a summary, the values contained into the table cannot be modified in this tab; in order to change the parameters, the correct Module Tab must be selected, and the settings must be adjusted there.

The Summary Tab is only available when the software is in Multiple Module Mode, since in Single Module Mode all the reported information is already presented in the unique Module Tab.

3 Using the FastGated Module

In this chapter, examples of measurements and configuration procedures of the FastGated SPAD are presented.

3.1 Powering on/off and operating the FastGated module

The following paragraphs illustrate some simple measurements in order to become familiar with the correct use and operation of the MPD FastGated Single-Photon Detection Module.

3.1.1 Preparation for use and powering on the module

Once verified that all the items listed in paragraph 1.2.1 have been bought, it is possible to start preparing the system using the following simple steps:

1. Install the Detection Head in the optical setup; the use of the MPD universal optical table adapter is highly recommended. Before installation, the cleanliness of the optical window of the detector should be checked, using the suggestions listed in paragraph 1.2.3.
2. Connect the Detection Head to the Control Unit by using the orange wide-bandwidth cable and inserting it in the inlets present in the back panel of both devices. It must be ensured that the latches are both locked in the correct position. Take care in cable routing: minimum bend radius is 50 mm and first bend must be at almost 100 mm from the end connector.
3. Connect the power cord between the power inlet in the back panel of the Control Unit and the power supply line.
4. Connect the USB cable from the Control Unit to the PC.
5. Switch on the Control Unit, using the ON/OFF switch on the rear panel.

After this last operation the fan starts rotating and the module is ready to accept commands from the PC controlling program.

3.1.2 Program start and device acquisition

By following the instructions outlined in Chapter 2, the control software can be installed in the computer and then started. After the splash screen, reporting the software version number, the *Start Tab* will be shown. The software automatically searches the connected modules at startup so, when the splash screen disappears, all the connected modules should be displayed in the *Detected Modules* table as shown in Figure 3; if this does not happen, by clicking the *AutoDetect* button, it is possible to force the program to retry the search.

For each connected module a custom name can be assigned. This is very useful for identifying the correct module inside the program when controlling two or more modules with one single program; however, the serial number of both Control Unit and Detection Head is also reported inside the *Module Tabs*. When all the connected modules are reported into the table and named, the *Accept Config* button has to be pressed. Now the custom names are stored in the PC and a module tab for each connected module is created (see Chapter 2 for a more detailed explanation).

3.1.3 Device configuration and detector turn-on

Before turning on the SPAD(s), for each tab relative to a connected module (or for the only visible window, when in *Single Module Mode*), these steps must be followed:

1. Make sure that *Detection Head LED*, *Control Unit LED* and *System Ready LED* are all green; they must remain green during all the system functioning. If they are not, see the paragraph 2.4.4 and 3.5 for troubleshooting.
2. Select a *SPAD Preset*, using the list-box shown in Figure 16. If *Custom Settings* has been chosen, enter the desired values:
 - Select a *Trigger source* (internal/external or *FreeRunning*) through the menu shown in Figure 11 and fill as desired the trigger related fields.
 - Enter a *Gate Width* and *Current* in the controls shown in Figure 15, if required.
 - Enter device temperature, excess bias, hold-off and avalanche threshold.

Completed these operations the *Apply Settings and Turn On SPAD* button can be pressed. In the next seconds all the status LED will be turned on, with the following sequence:

1. The *TEC Controller LED* will become yellow and then green; during the yellow phase the detector temperature, indicated by *SPAD Temp* field, will change from the current temperature (the ambient temperature if the detector has been left off for a long time) to the one that has been selected.

2. The *SPAD* LED will become first yellow and afterwards green when the right bias voltage has been applied to the detector.
3. The *GATE* LED becomes green to indicate that the gate signal is currently applied to the SPAD.

Now the module is ready to be used in the experimental setup. During the module functioning, the trigger and gate parameters can be easily modified, simply by changing them and uploading them to the module through the *Update Configuration* button. Before changing the *SPAD Preset* currently in use, the SPAD must be tuned off by using the *Turn Off SPAD* button.

3.1.4 End of measure and powering off the module

When the measurement ends and the FastGated Single-Photon Detection Module is not needed anymore, the module must be powered down correctly in order to prevent detector damages. The correct procedure is the following one:

1. Press the *Turn Off SPAD* button and wait until the SPAD LED goes off.
2. Repeat this operation for any connected module through the respective module tab.
3. When all the SPADs have been turned off, close the program. A message warns the user if there are modules still running when the software is closed. If this happens, please go back to the appropriate tabs and turn off these SPADs or **carefully** read the following chapter 3.1.5 if you want use them in the *standalone mode*.
4. It is now possible to press the power switch, located in the back panel of each module, in order to physically switch off the module.
5. Before powering on again a Detection Module, please wait for at least 20 seconds.

If the power switch is pressed before the closing of the software, a warning window will signal that there is a communication problem. This warning can, in this case only, be ignored.

3.1.5 Standalone module use (use with caution)

The FastGated Single-Photon Detection Module can also be operated without a PC constantly connected. In fact, with a properly configured and running module, it will keep running if the USB cable is detached. As soon as the USB cable is disconnected from the module with a biased detector, the SW will show a Communication Error: this signals that the module is still operating and that it has to be reconnected later to the PC in order to turn the SPAD off correctly. This is particularly useful when long measurements have to be performed and other instruments do not require a supervisor PC. However, the customer must be *careful* when this modality is used: the status of the module cannot be monitored through the control software

and, since the detector is biased, the module cannot be switched off through the power switch. In order to safely power off the system, the module **must** be reconnected to the PC, detected with the procedure described in Chapter 3.1.2 and correctly turned off using the procedure described in Chapter 3.1.4 (otherwise the SPAD might be *damaged*). If during the standalone functioning some errors occur, they will be reported after the device detection procedure.

3.2 Basic Setups

In this section simple test measurements are outlined and briefly explained.

3.2.1 Photon Counting setup

Photon-counting is the simplest measurements performable with the module and Figure 21 shows a possible example of an experimental setup. It consists of a continuous wave laser that produces photons at 680 nm, properly attenuated, and a sample that absorbs photons and re-emits at a slightly longer wavelength. These photons, properly collected, are sent to the SPAD detector (inside the Detection Head).

The module is configured to operate with the internal trigger and its Photon Out output is connected to a counter, that calculates the number of photons per seconds (i.e. counts per seconds, cps). As already explained in paragraph 1.5, since after every detected photon the SPAD must be kept disabled for a certain amount of time (hold-off time), the effective enabling frequency of the detector is not the *Gate Frequency*.

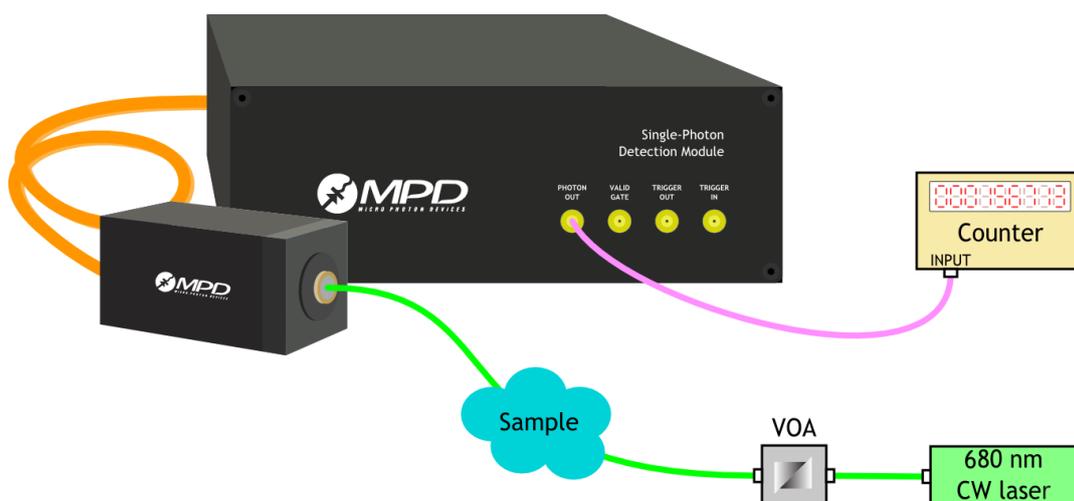


Figure 21. Simple setup for a Photon-counting measure (green: optical signals, pink: electric signals).

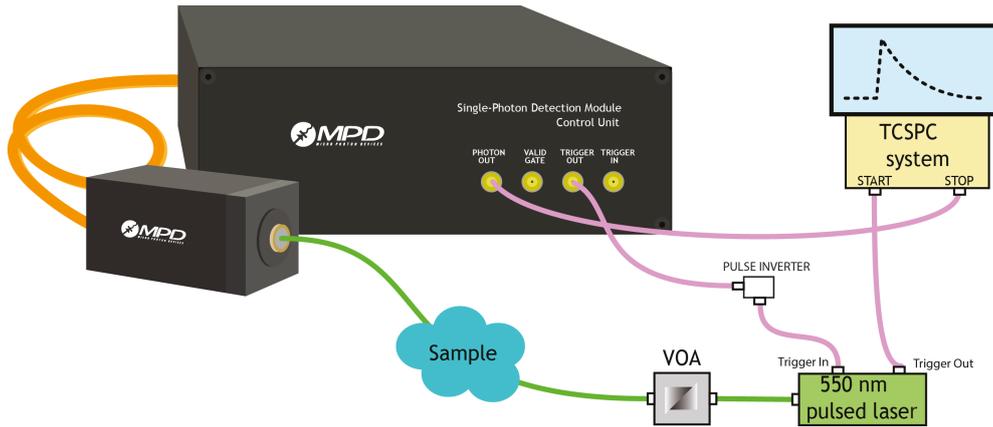


Figure 22. Simple setup for a photon-timing measure (green: optical signals, pink: electric signals).

We can simply estimate the effective trigger frequency f_{EFF} through the following simple formula:

$$f_{EFF} = f_{TRIG} \cdot (1 - CR \cdot T_{HO})$$

where f_{TRIG} is the *Gate Frequency* defined into the control software, CR is the count rate or the detected photons (indicated by the counter) and T_{HO} is the hold-off time, which is also defined through the control software. If we are interested in the number of photons that impinge on the sensor in a unitary time, we can use the approximate equation (see paragraph 1.5):

$$N_{PH} \cong \frac{T}{\eta(\lambda) \cdot T_{ON}} \cdot \frac{CR}{1 - CR \cdot T_{HO}}$$

where $\eta(\lambda)$ is the Photon Detection Efficiency of the SPAD at the operating wavelength and T_{ON}/T is simply the duty-cycle D at which the SPAD is switched on/off.

Of course, this configuration is highly academic: unless a few isolated cases, it is more efficient using a free-running detector with a CW photon source. Anyway, we strongly suggest to users that have never employed gated detectors to try and experiment with this very simple setup (even simply using attenuated ambient light as source).

3.2.2 Photon Timing setup

Another typical setup in which the FastGated SPAD is used is a photon-timing one, illustrated in Figure 22. This setup can be adopted for the measurement of fast waveforms of repetitive optical pulses. The technique is commonly known as Time Correlated Single-Photon Timing (TCSPC) and is extensively described in ref. [1] and [2]. This setup consists of a pulsed laser source that excites a fluorescent sample; the latter reemits photons with an exponential decay. In this example the module is still internally triggered but the Trigger Out of the module is connected to the trigger-in of the pulsed laser. In this way the laser is triggered by the FastGated module. This Trigger Out signal of the laser is then used, as START of a TCSPC system. The

STOP signal to the TCSPC system is given by the Photon Out of the Control Unit. Please note that it might be necessary to invert the Trigger Out pulse in order to synchronize the laser on the correct signal edge. For example, in case of a PicoQuant PicoHarp 300 [3], the laser sync is usually connected the Channel 0 input and the Photon Out is normally connected to the Channel 1 input. If the B&H SPC-130 [4] or similar cards are employed instead, please read carefully their manual because these cards work in the so-called reverse mode. When connecting all these instruments, it is very important to verify the voltage levels and the polarity of all the involved signals and to attenuate/invert them if necessary in order to comply with the inputs' absolute maximum ratings.

In order to ensure that the photons emitted by the sample impinge on the detector when the gate has been enabled, it is necessary to take particular care to the signal propagation delays inside the cables and in the instruments, included the FastGated control unit (see Chapter 4 for the actual numbers). This can be easily done by adjusting the connecting cable or fiber optics patches lengths.

Of course, even in this case all the equations used in the previous example are still valid and can be used in order to calculate the actual counting rate of the detector. Anyway, the TCSPC technique is normally adopted in order to correctly reconstruct the shape of the temporal response of fast pulses or a fast decaying fluorescence pulses (like in our example) by accurately measuring the photon arrival times and not simple measuring number of counts in a period of time. In order to do this, using the TCSPC technique, it must be guaranteed that only a single-photon reaches the detector for every single gate. This is commonly known in the scientific literature and is explained in ref. [1] and [2]. In order to avoid the pile-up effect [1] the detection rate of the laser trigger frequency must be lower than 5% (or better 1%). In this particular case, in order to obtain the correct equations, the module duty cycle D should not be considered: the reason relies in the fact that the Gate window is synchronized with the laser optical pulse and thus all the laser photons reach always the detector when the detector is on. Indeed, the correction due to the gate mode does not apply because for the laser pulses the SPAD behaves as if operated in free running. Only the correction for the hold-off time must be implemented. In addition, we will consider negligible the effect of the DCR and of the afterpulsing: the minor error that is committed is conservative in calculating the correct counting-rate for avoiding the pile-up effect.

In a gated mode TCSPC experiment, the 5% (1%) rule, described above, becomes that the light source must be properly attenuated in order to satisfy the following condition: the module count rate should be smaller than 5% (or 1%) of the valid laser frequency (f_{EFF}), i.e. the frequency calculated considering only the laser pulses that were shined when the module was in the ON state. The equation is:

$$CR < 5\% \cdot f_{EFF} = 5\% \cdot \left(f_{laser} - CR \cdot \frac{T_{HO}}{T_{laser}} \right) = 5\% \cdot (f_{laser} - f_{laser} \cdot CR \cdot T_{HO})$$

and thus simplifying:

$$\frac{CR}{1 - CR \cdot T_{HO}} < 5\% \cdot f_{laser}$$

Where $T_{laser} = 1/f_{laser}$, T_{HO} is the hold-off time and CR is the actual module counting rate as measured at a counter.

3.3 Advanced Setups

In this section two types of measurement, where the FastGated SPAD can be employed very effectively, are discussed.

3.3.1 Measuring a weak signal following a strong and very close (nanoseconds) peak.

For the sake of clarity let's describe this measurement set-up by focusing on a specific application: Diffuse Optical Tomography (DOT). Although this might seem too peculiar, the employed methodology in performing the measurement is general and can be successfully applied to other completely different fields of application.

DOT is used for medical imaging and a typical example is the measurement of the cerebral blood oxygenation even at depths of few centimeters. A pulsed light source (excitation) is used for injecting photons through the scalp into the brain, while the scattered back photons (signal) provide the means to probe different layers in the tissue and deep blood vessels. As depth sensitivity and high contrast can be achieved by placing the excitation point very close to the detection one, a challenge arises: as shown in Figure 23, the strong

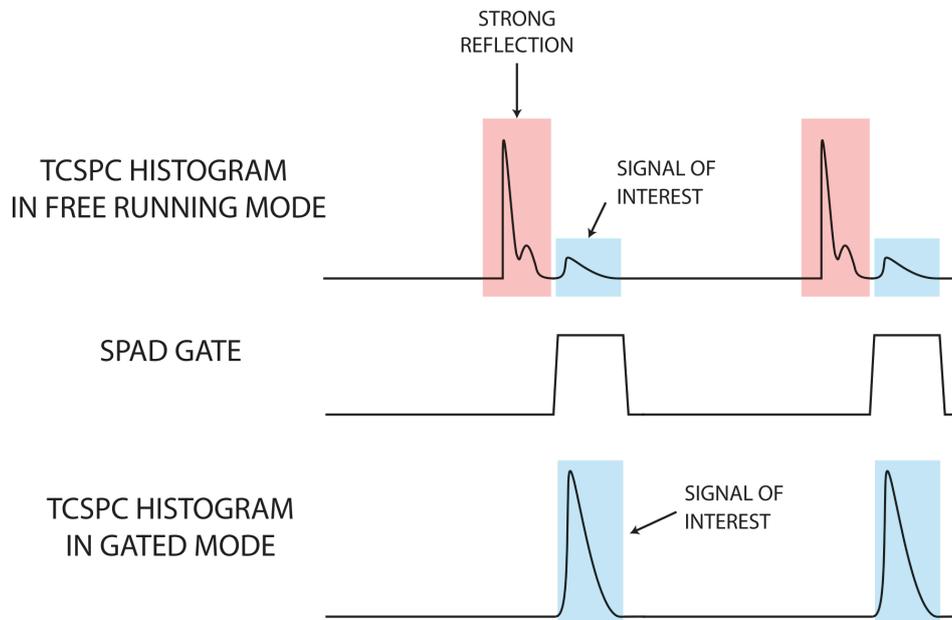


Figure 23. Strong light peak rejection by means of the time gated technique, in order to reveal a trailing weak signal.

presence of the “early photons” (i.e. those immediately reflected by the scalp, that show up as a high intensity light peak) severely limits the performance at small source-detector distance, since their number overcomes by many orders of magnitude that of “later photons”, i.e., those carrying the information. It is worth noting that in a non-line-of-sight (also known as “looking-around-the-corner”) application, the situation is similar: laser pulses are used to 3D-scan a scene by means of time of flight measurements; while the “first” photons to reach the detector are those reflected back by an object directly in front of it, the ones that arrive only few nanoseconds later, are those scattered back by the hidden objects to be revealed. Even in this case the situation is the one illustrated in Figure 23.

First of all, the presence of early photons imposes the need to reduce the optical laser power for avoiding detection system saturation. Furthermore, when using TCSPC techniques, the maximum count rate is typically limited by the so-called “pile-up” distortion effect, to a typical 5% maximum of the laser repetition rate. It might thus happen that, the power reduction is so high that the weak signal becomes so faint to be undetectable, either because it is entirely covered by noise or because the integration time, needed to accumulate enough late-photons for a good Signal-to-Noise Ratio (SNR), gets unbearably long (i.e. weeks).

If the strong peak could be eliminated, the laser power could be increased as the maximum count rate would be limited only by the signal to be measured. For example, if the strong peak would have a different wavelength respect to the signal (like in case of Raman scattering), then it could be possible to spectrally filter out the first one by means of a suitable optical filter (for example by using a bandpass one centered around the signal bandwidth). In the examples described above, unfortunately, both the strong peak (early photons) and the weak signal (late ones) have the same wavelength and thus, the former can only be temporally filtered, i.e. by using a detector that can be kept switched off during the arrival of the strong peak and immediately switched on when late photons arrive: a **gated** detector. Additionally, since the separation in time between the former and the latter can be of few nanoseconds or less, a FastGated detector must be used, as such module employs a sensor with on-off transition times in the order of hundreds of picoseconds.

It is clear thus that the FastGated Module can reject strong optical reflections or strong signals correlated with laser sync that don't provide any information, enhancing the SNR and the measuring time.

A typical application set-up is shown in Figure 24: laser trigger out is connected both to the START of the TCSPC system, and to the Trigger In of the FastGated Module, through an adjustable delay path. The fixed delay path can be obtained by means of cables between laser Trigger Out and SPAD Trigger In or with the MPD Picosecond Delayer for an easier fine adjustment. Of course, the STOP signal at the TCSPC system is provided by the FastGated module. Finally, the variable optical attenuator (VOA) is used for setting the laser power so that the pile-up effect is avoided.

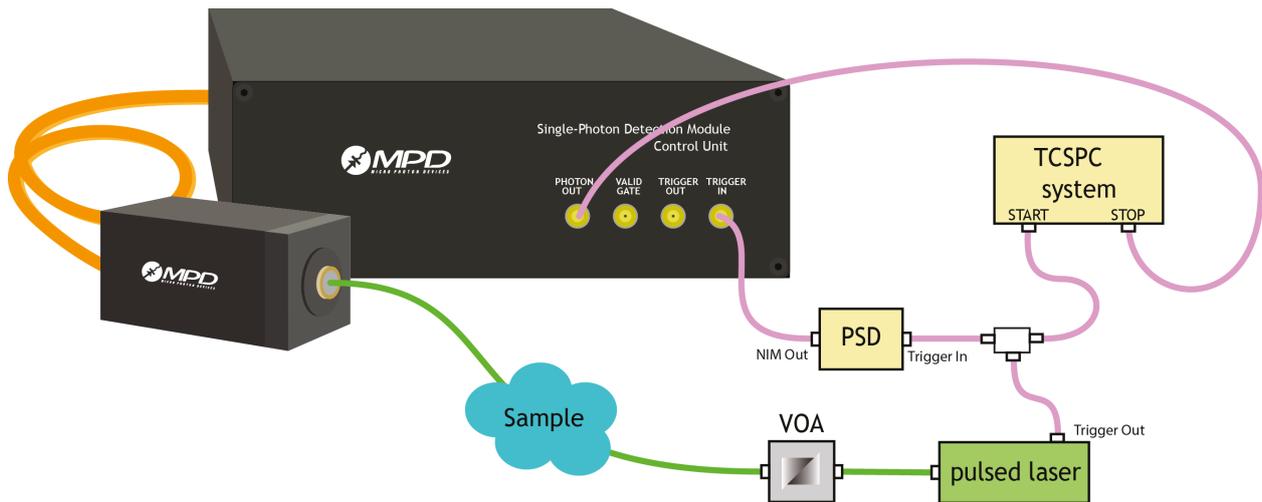


Figure 24. Advanced setup that allows to remove a strong unwanted signal near a faint interesting signal (green: optical signals, pink: electric signals).

To avoid errors, the following steps are recommended:

- Sets the FastGated Module in Free Running Mode;
- Acquire a TCSPC histogram and localize the unwanted high peak position in time;
- Change the module mode of operation to Gated Mode;
- Adjusts the delay time between the laser sync and the SPAD gate width, in order to enable the SPAD only after the unwanted high peak (early photons);
- Adjusts the SPAD gate width to terminate the gate window when the signal to detect is over or, at least, before the start of the following peak generated by the pulsed laser;
- Adjusts the FastGated Module parameters to get the best results for your application.

As further readings we suggest references [5][6].

3.3.2 High Dynamic range setup

In many optical applications, the Dynamic Range (DR) plays an important role in the extraction of information of the physical processes under investigation. Since DR is essentially the ratio between maximum and minimum detectable signal intensities, the DR upper limit is normally given by the saturation level of detection electronics, while the lower limit is usually set by background noise, e.g. at the level where Signal-to-Noise Ratio (SNR) approaches unity. Unfortunately, in TCSPC application the maximum counting rate is limited by both the saturation of the detection electronics and the “pile-up” distortion effect. Therefore, the optical power injected into the medium must be reduced of various orders of magnitude in order to avoid such saturation. As a consequence, in order to be able to acquire a high dynamic range decay curve, a high integration time is required for collecting enough photons in the low signal regions.

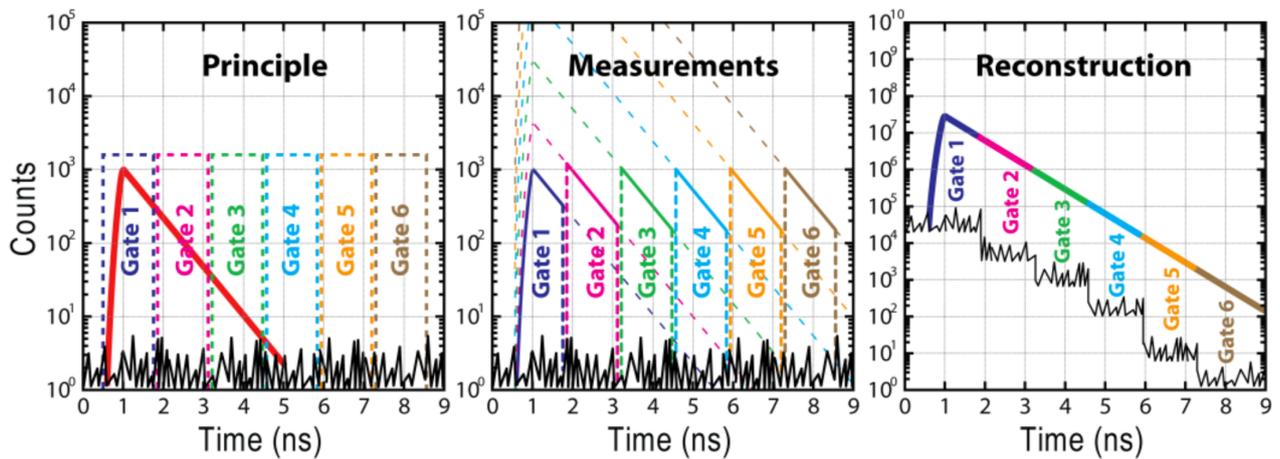


Figure 25. Schematic representation of the method used for reconstructing a curve with high dynamic range when acquired in slices [7].

This limitation can be overcome by using the FastGated Module. In this case, the curve can be collected by acquiring many slices of it, with different delays and power intensities; then the curve is reconstructed by combining the acquired slices, after amplitude normalization according to the different power intensities. More in detail [7], Figure 25(left) shows how the waveform to be acquired (red curve) is divided in many slices (i.e. Gate1, Gate2, etc.) at different delays. By turning ON the detector during the first gate (Gate1), the first part of the curve is acquired with a certain optical power (Figure 25, center).

Then, by increasing the gate delay, a second part of the curve is acquired (Gate2), where the optical signal is weaker and, therefore, the optical power can be increased (Figure 25, center). By repeating such procedure many times, many slices are acquired at progressively higher optical powers. Finally, the slices are normalized on the basis of the optical power and are combined together in order to reconstruct the whole waveform (Figure 25, right). As shown, by increasing the signal level (i.e. the optical power) at longer delays, the characterization of the curve tail was improved, thus achieving a very high DR because the noise (also represented in Figure 25) is not the same along the curve. Indeed, the signal-to-noise ratio in each slice, before normalization, is always the same, and it is that of a standard TCSPC measurement. But in the slices that acquire the tail, the signal has been greatly amplified because the gated detector is not overwhelmed by the many photons of the peak. However, after power normalization and waveform reconstruction, the noise level at the beginning of the reconstructed curve is higher than that at the end of the curve (see Figure 25, right).

The typical application set-up is the same as the one discussed in paragraph 3.3.1 with the following differences:

1. The delay must be generated by a MPD Picosecond delay as it must be adjustable.
2. The variable optical attenuator must also be programmable as it must be programmed accordingly with the gate shifts as described above.

In order to avoid errors, the following steps are recommended:

- Set the FastGated Module in Free-running Mode;
- Acquire a TCSPC histogram for localizing in time the signal to be detected;
- Set the FastGated module in Gated Mode;
- Set the Picosecond Delayer delay so that the gate rising edge of the detector starts 1-2 nanoseconds before the curve decay rising time;
- Set the SPAD gate width longer than the chosen slicing window width;
- Start the measure cycling the following steps:
 - Adjust the laser power by means of the VOA. Power can be increased up to the pile-up effect limit, i.e. module count rate up to the 5% of laser repetition frequency;
 - Acquire the curve slice;
 - Set the Picosecond Delayer delay for the next step;
- Reconstruct the full waveform by summing together the various slices (or a selected part of them) after power normalization.

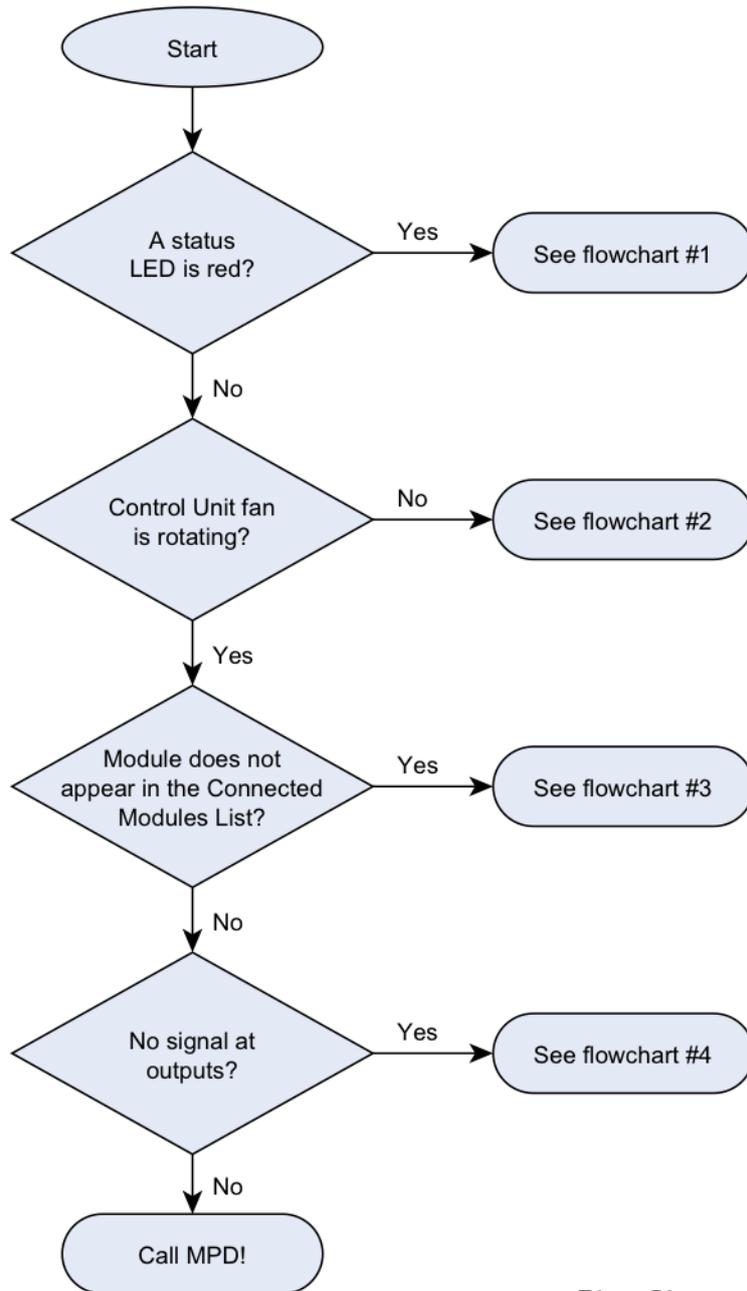
As further readings, we suggest reference [7].

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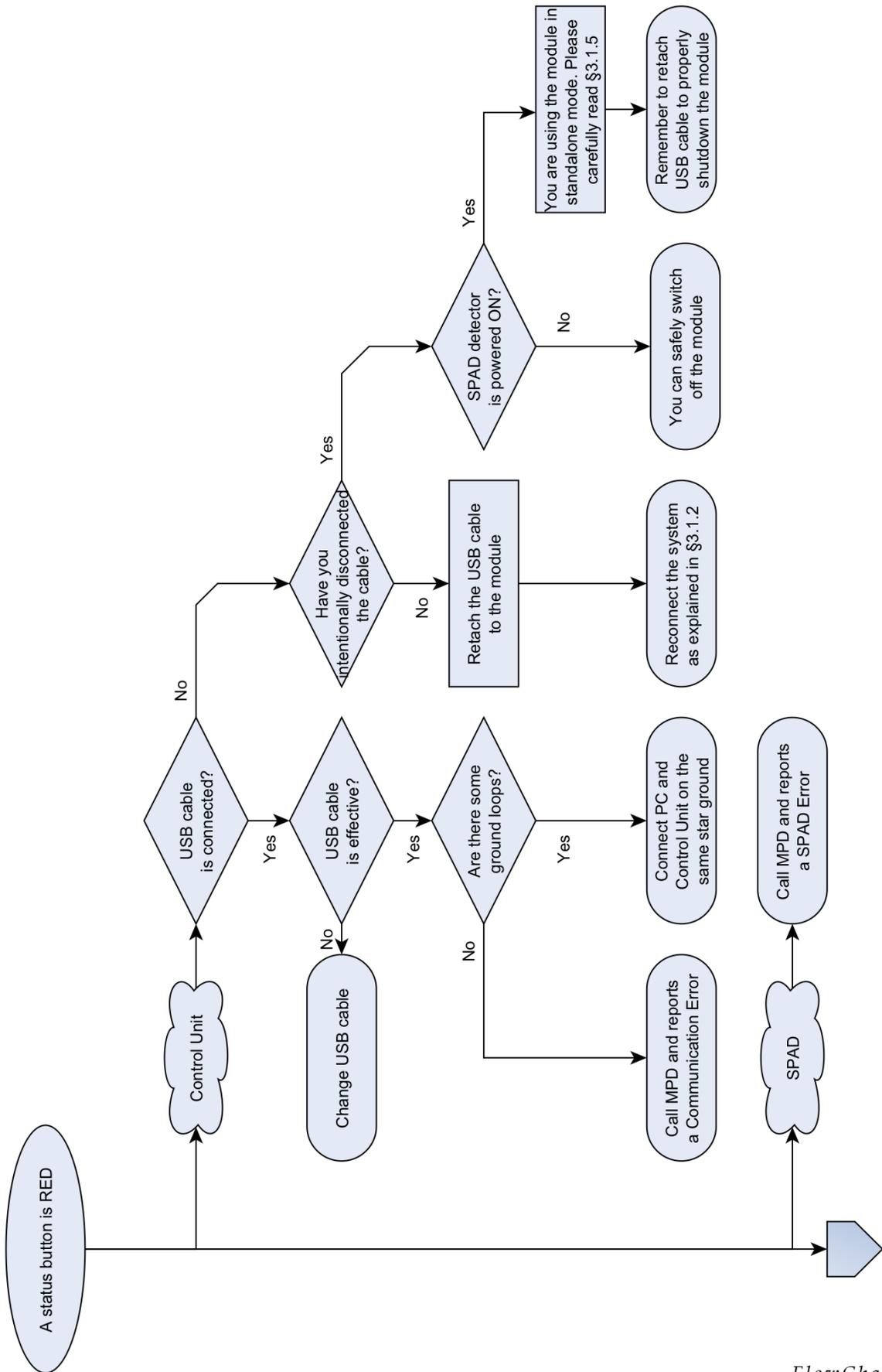
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<https://www.picoquant.com/products/category/tcspc-and-time-tagging-modules/picoharp-300-stand-alone-tcspc-module-with-usb-interface>
- [4] SPC-130-emn by Becker and Hickl GmbH.
<https://www.becker-hickl.com/products/spc-130-emn>
- [5] A. Pifferi, A. Torricelli, L. Spinelli, D. Contini, R. Cubeddu, F. Martelli, G. Zaccanti, A. Tosi, A. Dalla Mora, F. Zappa, and S. D. Cova, "Time-Resolved Diffuse Reflectance Using Small Source-Detector Separation and Fast Single-Photon Gating," Phys. Rev. Lett., vol. 100, no. 13, Mar. 2008.
- [6] M. Buttafava, J. Zeman, A. Tosi, K. Eliceiri, and A. Velten, "Non-line-of-sight imaging using a time-gated single photon avalanche diode," Optics Express, vol. 23, no. 16, pp. 20997–15, 2015.
- [7] A. Dalla Mora, A. Tosi, F. Zappa, S. D. Cova, D. Contini, A. Pifferi, L. Spinelli, A. Torricelli, and R. Cubeddu, "Fast-Gated Single-Photon Avalanche Diode for Wide Dynamic Range Near Infrared Spectroscopy," vol. 16, no. 4, pp. 1023–1030.

3.5 Troubleshooting

Whenever a problem occurs during the use of the FastGated Module, please follow the directions contained in FlowChart #0. Please contact MPD for assistance only if your problem is not listed here, if the flowchart directly tells you to do so or if the error persists despite the troubleshooting efforts.

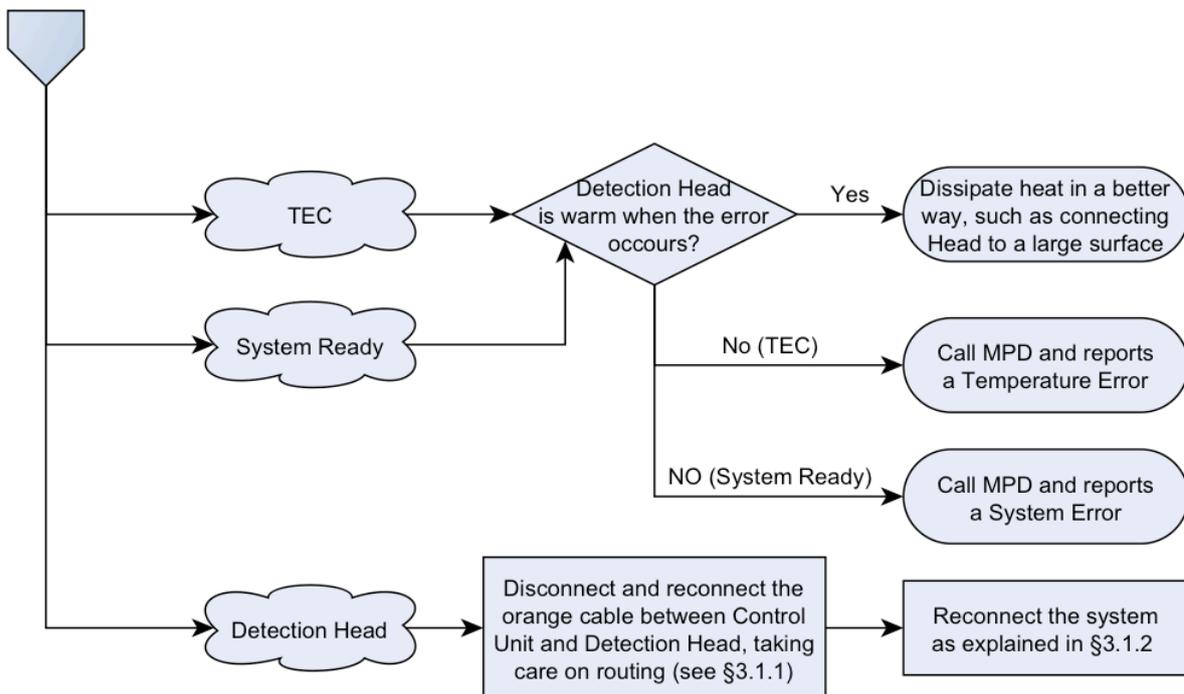


FlowChart #0

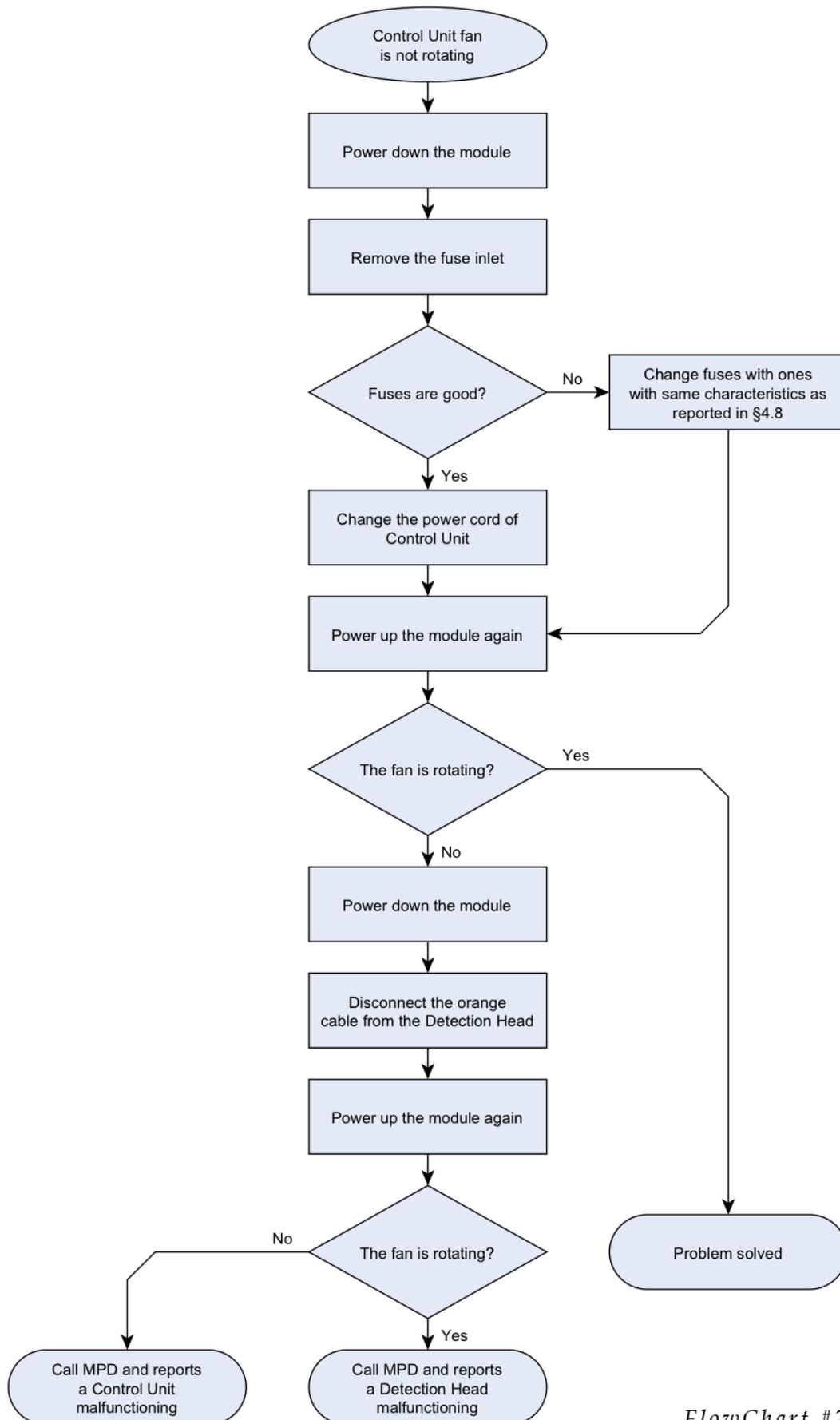


FlowChart #1

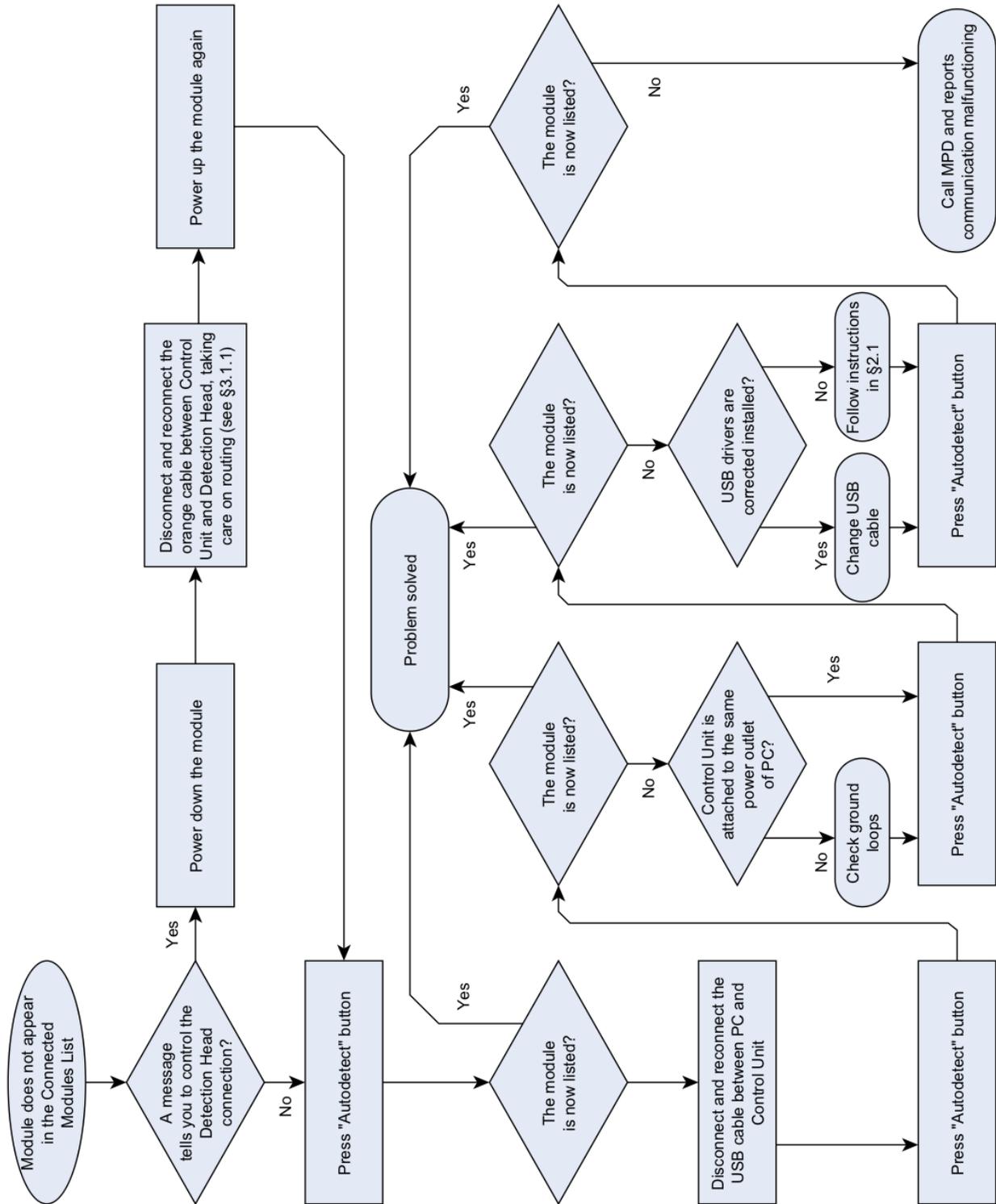
continue from previous page



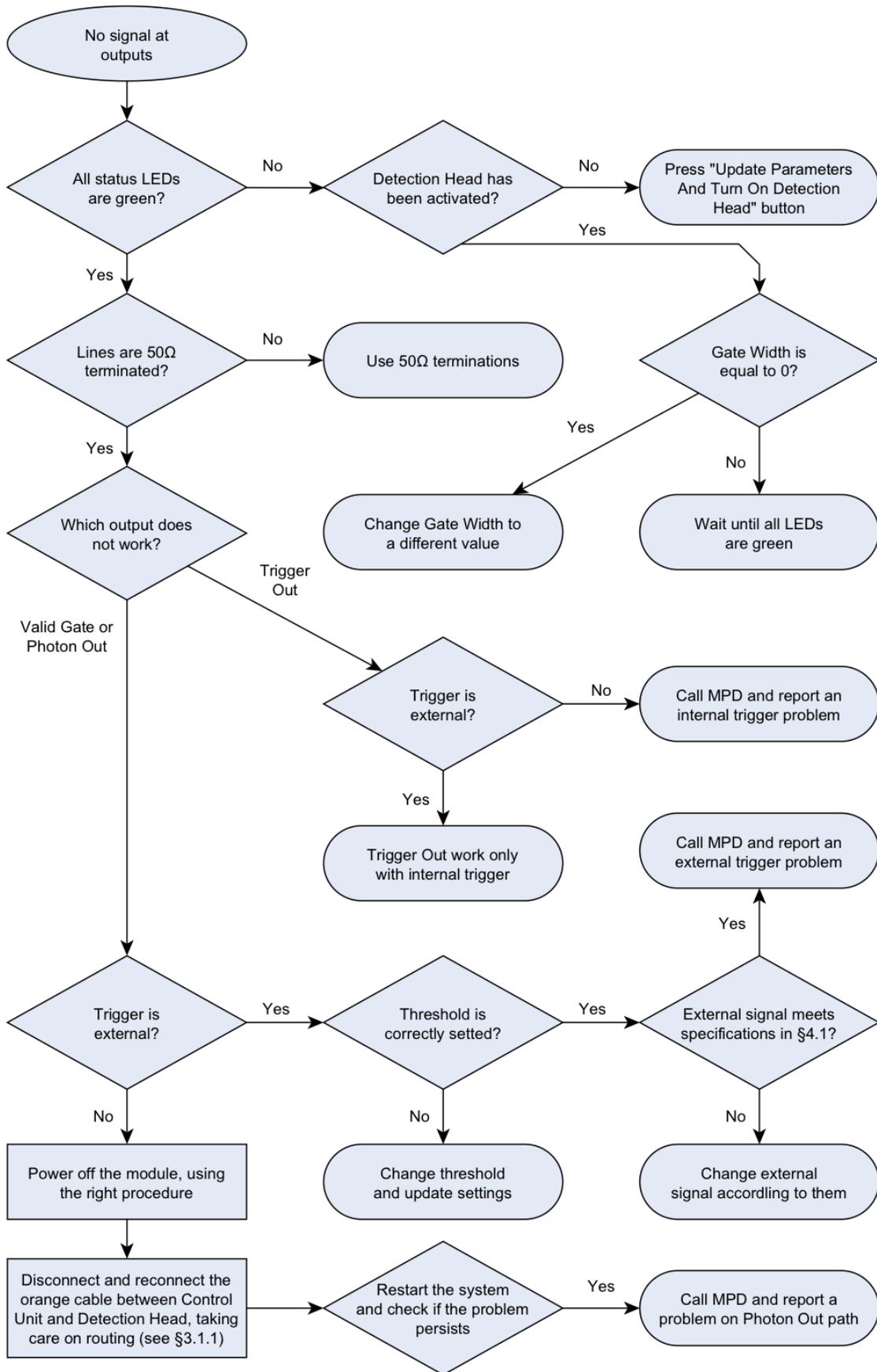
USING THE FASTGATED MODULE



FlowChart #2



FlowChart #3



FlowChart #4

4 Specifications

The specifications of the FastGated Single-Photon Detection Module are provided in this chapter.

4.1 Instrument Input (Trigger IN)

Note: Unused when the module is in Free-running or in internal trigger mode.

Impedance	50 Ω	
Coupling	DC	
Frequency Range ¹	DC to 80 MHz	if $T_{ON} \leq 10$ ns
	DC to 25 MHz	if $T_{ON} > 10$ ns
Input Level	Range:	-2 V \div 2.5 V
	Damage:	± 5 V
Minimum Slew Rate	5 V/ μ s	
Threshold Level	Range:	-2 V \div 2.5 V
	Resolution:	18 mV
	Accuracy:	± 30 mV
Trigger Slope	Positive or Negative	
Minimum Pulse Width	2 ns	

4.2 Instrument LVTTTL Outputs (Trigger Out – Valid Gate)²

Note: disabled when the module is in Free-running or external trigger mode.

Amplitude	0 \div 2.9 V \pm 400 mV
Required Load	50 Ω fixed DC impedance
Rise/Fall Time (20 \div 80 %)	4 ns
Valid Edge	Positive

¹ Maximum frequency also limited by condition $1/f_{TRIG} > T_{ON} + \text{min. GATE-OFF time}$ (see paragraph 4.5)

² See paragraph 4.5.

SPECIFICATIONS

- TRIGGER SIGNAL:
 - in *gated mode*, it is the signal designated to be the reference; it could be the internal trigger or the external one supplied by the user. Note that the delay varies according to the selected trigger source. Anyway, reported delays are related to the respective front panel measured signal (i.e. Trigger Out or Trigger In);
 - in *free-running mode*, this signal is disabled, the SPAD is always on, it is quenched only if an avalanche occurs and it is enabled immediately at the end of each hold-off time.
- GATE WINDOW:
 - in *gated mode*, it is the SPAD enable signal, measured directly on the detector. Note this signal cannot be directly measured by the user;
 - in *free-running mode*, the “Gate” signal is off during the hold-off time only, otherwise it is on.
- AVALANCHE SIGNAL: it is the SPAD output signal, asserted when a photon is absorbed and detected by the device. This is an internal signal that cannot be measured by the user.
- PHOTON OUT: it is the front panel output which marks a detected photon.
- VALID GATE:
 - in *gated mode*, it is the front panel output which reports which Gate windows are effectively applied to the SPAD and are not masked during the hold-off time. Normally *Gate Frequency* and Valid Gate are matched, but during hold-off time the *Gate Frequency* (trigger signal) is masked and this output remains into the low logic state (see paragraph 1.5 of the gated mode user manual). Please note that due to the limited rise/falling times of this signal, at very high-frequency/short gate times, this signal may not reach the full amplitude, specified in 4.2. In addition, the width of this signal can slightly differ from the actual gate pulse applied to the SPAD detector. Since in the most typical uses of the fastgated module, the user would be in these conditions, it is recommended either not to use the VALID GATE or to understand very well all its limitations. MPD is available any time to help via email at info@micro-photon-devices.com
 - in *free-running mode*, the Valid Gate signal outputs the effective SPAD status, i.e. when it is on or off due to the hold-off.

Table 2. Signal propagation times into different operating conditions.

Condition		t ₁	t ₂	t ₃
External Trigger	T _{ON} ≤ 10 ns	29.0 ns ± 10%	10.7 ns ± 10%	14.0 ns ± 5%
	T _{ON} > 10 ns	54.5 ns ± 10%		
Internal Trigger	T _{ON} ≤ 10 ns	27.0 ns ± 10%		
	T _{ON} > 10 ns	52.5 ns ± 10%		

SPECIFICATIONS

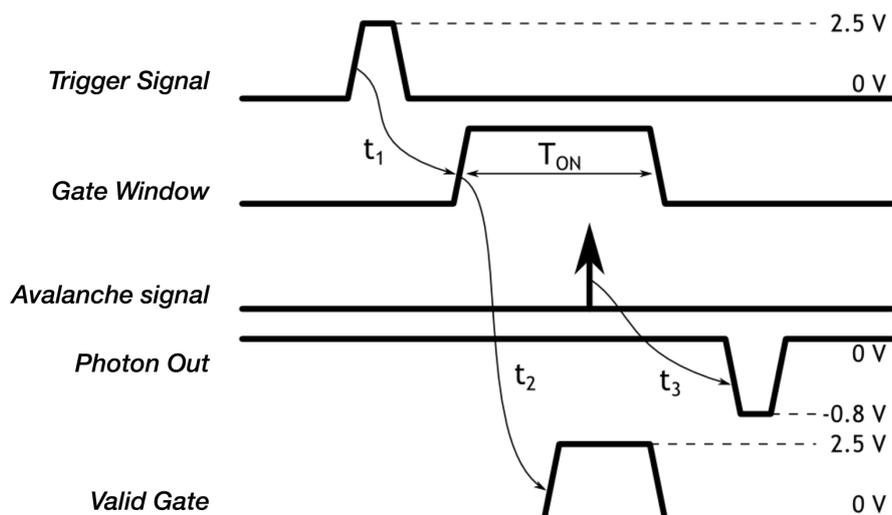


Figure 26. Signals waveform, with delay times highlighted.

4.7 Detector

Detector size	50 μm diameter	
Photon Detection Efficiency (typ @ $V_{EX} = 5\text{ V}$)	@ 320 nm: 25% @ 400 nm: 50% @ 650 nm: 14% @ 800 nm: 4%	
Temperature range	-10 $^{\circ}\text{C}$ \div 30 $^{\circ}\text{C}$ Detector minimum temperature may depend both on operating environment temperature and Detection Head case power dissipation. Please improve thermal conduction if a TEC Error occurs.	
Temperature resolution	0.1 $^{\circ}\text{C}$	
SPAD performances	Max DCR (@ $T = 25\text{ }^{\circ}\text{C}$, $V_{EX} = 5\text{ V}$)	< 200 c/s
	Typ. FWHM (@ $V_{EX} = 5\text{ V}$)	< 60 ps
Maximum Optical Power	1 mW (CW – Continuous Wave)	
The Silicon SPAD is not damaged by accidental exposure to room light. However, it is preferable not to keep the detector in such condition for prolonged time.		
Optical Interface (free space)	SPAD sensor surface is placed 2.4mm \pm 0.4mm from the window cap top glass surface.	

4.8 General Specifications

Control Unit Dimensions	235 mm x 250 mm x 90 mm
Detection Head Dimensions	60 mm x 60 mm x 120 mm
Weight	2.5 kg maximum
Power Supply Voltage	100 to 240 VAC – 50/60 Hz
Continuous Power Requirements	40 VA maximum
Power-Line Fuse	1 A, 250 V
Operating Environment	10 °C to 25 °C
Storage Environment	0 °C to 70 °C
Remote Interface	USB 1.1

4.9 System Requirements for Software

Operating system (Microsoft® Windows® only)	<ul style="list-style-type: none"> • 10/8/7/Vista: both 32 and 64 bit • XP/Server 2003 R2: only 32 bit • Server 2008 R2: only 64 bit
Minimum recommended system requirements	<ul style="list-style-type: none"> • Pentium 4 or equivalent processor • 500Mb or 1 GB of RAM • 1 GB of free disk space • 1024 x 768 pixel display resolution • USB 1.1 or newer port

5 Changelog

- 5.0.1 First Version.
- 5.0.8 Corrected various errors related to the InGaAs/InP module, introduced significant examples. Useful set-up has been added.
- 5.0.9 Updated signal propagation delays.
- 5.0.10 Modified hold-off time range. Minor corrections in main text.
- 5.0.11 Updated Fig.1, gate-risetime and LVTTTL outputs specifications.