BRIDGEPORT INSTRUMENTS, LLC
NUCLEAR RADIATION DETECTION

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MCA-3000 Users Manual

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Summary

The MCA-3000 is a family of high-performance multi-channel analyzers (MCA) for measuring gamma-ray radioactivity with a scintillator.

The PMT-3000 includes a operating voltage supply and plugs directly onto a photomultiplier.

The SiPM-3000 includes the SiPM operating voltage supply and plugs directly onto an SiPM-array.

Using its embedded 32-bit ARM processor, it provides accurate gamma-ray spectroscopy and gain stabilization together with many advanced features such as automatic background subtraction and alarm computations.

This document describes how to use the MCA-3000 from the graphical user interface and from Python scripts. Using the MCA Data Server, developers will find they can program the MCA-3000 in any language they want.

Feature summary – PMT-3000

- More than 4Mcps histogramming rate
- Suitable for all scintillators via programmable integration time
- Positive and negative operating voltage and different PMT pinouts.

Feature summary – SiPM-3000

- Suitable for 500kcps on NaI(Tl) or faster scintillators
- Suitable for many scintillators via programmable integration time
- Very low-noise integrated SiPM voltage supply
- Very low trigger threshold: <10keV with 2MeV energy range.

Feature summary – Common characteristics

- Histogram: 4K×32; Loss-less two-bank mode with 2× 2K×32;
- List mode, pulse shape capture
- On the fly pulse shape discrimination
- Built-in programmable gain stabilization performed by embedded ARM processor
- USB interface; Serial interface on PCB; default 115200 baud
- FPGA customization possible for application specific product
- ARM C-code customization possible for application specific product
- Software updates via USB
- Power consumption is only 300mW (5V@60mA)

Popular FPGA firmware options

- Loss-less dual bank list mode buffer with 2047 events per buffer.
- 100ms time slice operation with 20-deep buffer, events and 1k histogram per slice.

Popular software options

- Sample vs background measurements with alarm computation
- Radiation Portal mode with automatic background tracking and programmable alarm

Table of Contents

1. Supporting Documentation

Open-source software The software is open source and mostly written in Python. Bridgeport Instruments provides a software installer, which by default will create a C:\BPISoftV3 directory. That folder includes Python 3.7 with three added packages: ZMQ (www.zeromq.net), wxPython and Matplotlib v 3.2. ZMQ is used to implement the client-server behavior and it is accessible from more than 40 programming languages. Matplotlib is used for the graphics interface, and wxPython is used to create a traditional user interface with pull down menus.

The wxMCA folder that contains the MCA software can be placed anywhere on the hard disk. Inside is a folder called documentation and the best starting page is wxMCA/documentation/english/introduction/introduction.html which you can open in any web-browser. This set of linked documents contains a description of every control variable and every data field used by the MCA-3000.

2. Getting started

2.1 Using the USB interface

For USB communication the MCA-3000 uses libusb0.1 (Linux) and libusb_win32 on Windows 10. The Windows 10 libusb dll is digitally signed. When the MCA hardware is present during the installation, the installer will automatically link the MCA-3000 to libusb_win32.

However, it is also possible to simply copy the BPISoftV3 folder onto the C: drive and install the Windows USB-driver manually. This needs to be done only once, and Windows will later recognize any other MCA-3000, by its USB vendor ID of 0x1FA4 and the USB product ID of 0x0103 (PMT-3000) or 0x203 (SiPM-3000).

Open the Windows Device Manager and connect the MCA-3000 to a USB port. Wait until it appears in the Device Manager as an unknown device of type armMorpho or sipmMorpho.

Open the C:\BPISoftV3 folder and launch zadig-2.4.exe. Use Options/List All Devices to refresh the device list and select the select the device with the BPI vendor ID of 0x1FA4. To the right of the green arrow, select libusb-win32 (v 1.2.6.0) and click the big 'Install Driver' button below. Note that it may take up to 20 seconds for the screen to update - be patient. Once the 'Driver Installation Successful' message appears you can close the window. In the Device Manager you will now see the MCA-3000 listed under 'libusb-win32 devices'.

2.2 Launching the software

First launch the MCA Data Server. Look inside the wxMCA folder. Under Windows, double-click on run_mds.cmd. Under Linux, launch wxMCA/mds/mds_server.py making sure you use a python 3.7 or higher installation

that also includes ZMQ, wxPython and Matplotlib.

If the MDS reports no MCA found, the OS may have been slow in enumerating the MCA on the USB bus. Kill the MDS and launch it again.

Then launch the User Interface. Under Windows, double-click on run_wxMCA.cmd. Under Linux, launch wxMCA/wxGUI/MCA_Main.py

The items in the menu bar are mostly self-explanatory. You can view results and edit instrument settings in a spread-sheet environment. To send the changed values to the instrument, you need to click on File →to MCA.

3. Energy Spectrum

The MCA provides fast and accurate measurements of energy spectrum and count rates. To acquire an energy histogram, select Display→Histogram from the menu bar. In response, a histogram panel will open. On that panel use "New" to erase the old histogram and count rate data and begin a new acquisition. The panel does not automatically refresh, so click the "Refresh" button to get an updated energy spectrum.

Use (Save) to append the energy histogram and count rate data to a data file.

3.1 Adjusting operating voltage

You need to set the electronic gain and adjust the operating voltage to set the maximum measurable energy.

Then adjust the digital gain to achieve the desired MCA calibration in keV per bin

The maximum measurable energy is independent of the number of histogram bins used. Users need to adjust the operating voltage to change the gain of the SiPM or PMT. In the table below we recommend maximum measurable energies for different applications.

Max. Energy	*Comment*
1.0MeV	High gain for measuring low energies down to 20keV. Good for measuring contamination with Cs-137 and Cs-140 (fresh fission product), or Radium isotopes.
2.0MeV	Measure NORM up to K-40 at 1460keV
3.0MeV	Wide range covers all naturally occurring gamma-rays, even Tl-208 at 2615keV

Table 1: Cs-137 calibration for different tasks; NORM: Naturally occurring radioactive materials

How to determine the maximum measurable energy. In the (fpga_ctrl) display set ha_mode to 1 to measure the pulse height. The maximum measurable pulse height is 900. Start a new histogram and record the peak position (P) of a known isotope; eg E=662keV of Cs-137. The maximum measurable energy is computed as

$$E_{\max} = E \cdot \frac{900}{P}$$

Hence, putting the pulse height peak of Cs-137 at 187mV will result in a maximum measurable enery of 3.18MeV.

There are four discrete electronic gains that can be applied. In (fpga_ctrl), select gain_select = 1, 2, 4, or 8 for increasingly higher electronic gains. Note that the highest electronic gain will slow down the input amplifier response and is usually only used for slow scintillators, such as CsI(Na).

For a continuous and smooth gain change, vary the operating voltage to move the pulse height peak. Access the operating voltage control by opening the (arm_ctrl) display. Enter a new operating voltage in the cal_ov field and hit enter. Use File→To MCA to write the voltage to the MCA.

Go back to the (Histogram) display and click (New) to start a new acquisition. If you change the operating voltage by 1%, the PMT gain will change by about 6%. For the SiPM-3000 the gain equation is

$$\text{gain} = 1.0\text{e}6 \cdot (V - 28.6\text{V})$$

Once the pulse height peak is in the right position and therefore the maximum energy has

been set, keep the operating voltage and the electronic gain constant.

Now adjust the digital gain to achieve the desired MCA calibration in keV per bin. Once the operating voltage has been established, set **ha_mode** back to 0, and start a new histogram

Determine the measured peak position (P) and use the desired peak position (E) to determine the new ***digital_gain***

$$dg_{\text{new}} = dg \cdot \frac{E}{P}$$

With that the detector has been calibrated. See the calibration section 4 for a much more detailed description.

3.2 Count rate measurement

Observe how the count rate accuracy improves with measurement time. The MCA reports count rates together with their statistical errors. This gives users a useful tool. Manually, or programmatically, they can end a measurement precisely when the desired accuracy has been reached, which saves time and money.

The error (in %) is computed from the number of events as 100×2/sqrt(N), where N is the number of events. This is called the statistical 2-σ error. The true count rate lies within this error range with a 95% probability.

Note that the MCA corrects the recognized count rate using the known dead time per event. Hence the reported count rate is greater than the recognized count rate. The reported count rate is also an accurate estimate of the true number of counts per second. In fact the reported count rate should match the true input count rate with about 1% accuracy (systematic error) for input count rates up to 100kcps. The statistical count rate error is computed correctly using the number of recognized events.

3.3 Histogramming speed

The MCA has a non-extendable dead time equal to the hold_off_time per recognized event. For NaI(Tl) between 5°C and 65°C the MCA-3000 recommends a fixed hold off time for NaI of 1.2µs. The resulting throughput is shown in the next figure.

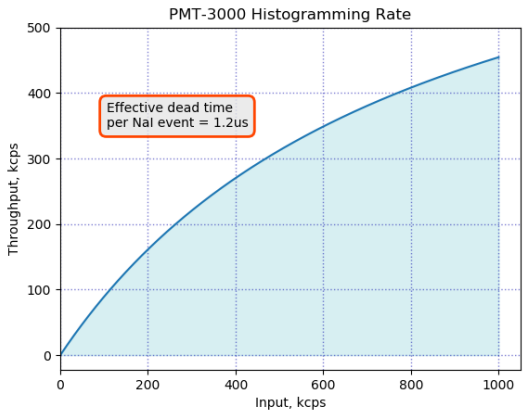


Fig. 1: Expected histogramming rate vs input count rate for a hold_off_time = 1.2µs; (ie typical for NaI(Tl) at room temperature.

The SiPM-3000 will match the speed of the PMT-3000 for NaI. For $LaBr_3$ the PMT-3000 can go even faster – at a fixed hold off time of only 0.3µs. The resulting throughput is shown in the next figure.

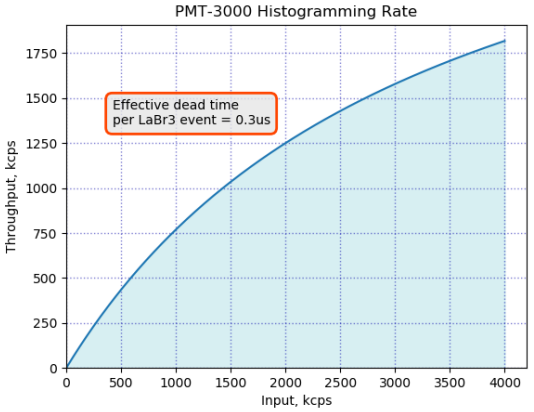


Fig. 2: Expected histogramming rate vs input count rate for a hold_off_time = 0.3µs; (ie typical for $LaBr_3$.

3.4 High count rates

There may be a small gain shift at high count rates. Users should be aware that at input count rates above a few 10kcps there may occur small gain shifts in the energy spectrum. Typically, at 50kcps the gain may fall by about 1%, but the exact gain shift will depend on the PMT that is used on the detector.

4. Calibration

4.1 Theory of operation

The MCA-3000 uses a switched-gain input amplifier stage followed by an ADC with a 1V input range. The ADC samples the amplifier

output voltage at a rate of typically 40MSPS. In the PMT-3000, the sampling rate can reach 120MHz.

For proper operation, the amplifier output voltage must fall within the 1.0V input range of the ADC, as shown in the two figures below.

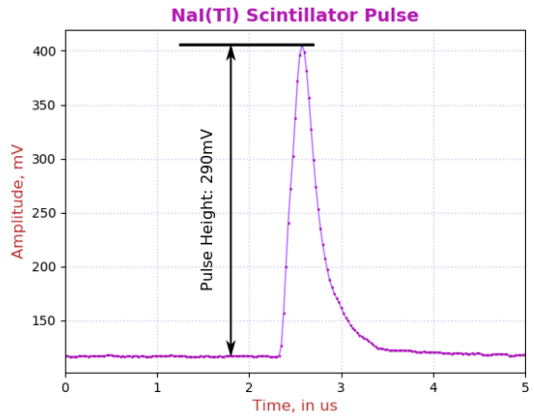


Fig. 3: A regular NaI(Tl) pulse.

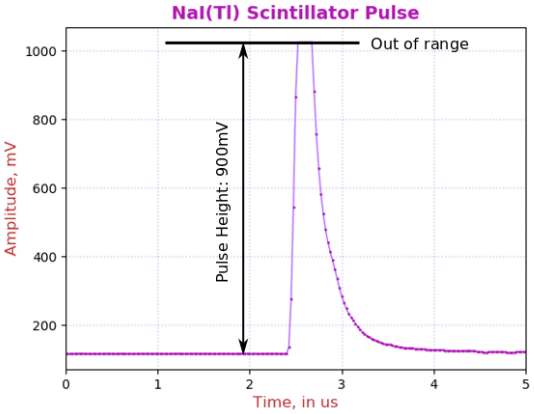


Fig. 4: An out of range NaI(Tl) pulse. Note how it cannot reach beyond 1023mV.

Pulse height is a measure of the difference between the maximum pulse voltage and the baseline from which it rises.

There is a built-in DC-offset of around 128mV and the maximum measurable voltage is shown as 1.023V. Hence the maximum practical signal pulse height range is around 900mV.

The first step of calibration at a chosen electronics gain, is to make sure that the maximum wanted energy can be measured by the ADC. At a fixed electronics gain, the applied operating voltage will determine the maximum measurable energy.

A very common calibration is to set the operating voltage such that the full-energy peak of Cs-137 (661.66keV) corresponds to a pulse height of 187mV. The maximum measurable energy is then 900mV/187mV×662keV=3.18MeV.

After adjusting the high voltage to set the maximum measurable energy, the user can now vary the digital gain to map the entire energy spectrum into an energy histogram of the desired size and calibration.

For example, we assume 40MHz ADC sampling rate and the recommended integration time of 1.2µs for NaI(Tl). We also assume that the Cs-137 662keV peak has an average pule height of 187mV. In that case, choose a digital gain of 4700 to place the peak in the energy histogram at 662keV, ie have an MCA calibration of 1.0 keV per bin.

Below we describe the calibration steps in detail.

4.2 Calibration file

Calibration controls are in autocal.json. This file can be found in the ./rad_config/Matplotlib_gui/config/ folder. Its contents are explained in the table below.

Variable	*Description*
cal_energy	The energy, in keV, for the calibration peak; eg 662 for Cs-137.
cal_pulse_height	The pulse height for the calibration peak; eg 187 for Cs-137 and 3.2MeV maximum measurable energy.
auto_update	0→ Off; 1→ Apply the new operating voltage and restart the mcaafter user clicks on "Calibrate" button.
keV_bin	Desired MCA calibration, as keV per MCA bin.
gain_exp	PMT's have a power law for their gain vs voltage function: $$\frac{gain}{gain_0} = \left(\frac{HV}{HV_0}\right)^{\text{gain\_exp}}$$ Typical values are 5.6 for R6231, 6.0 for CR105 and 7.5 for many other 10-stage PMT. For SiPM this parameter is ignored.
mass	The mass of the NaI crystal, in kg; used for computing the deposited dose rate from the count rate and deposited energy.

Fig. 4: The autocal.json data explained.

For use with Broadcom SiPM we use the following gain formula:

$$\text{gain} = 1.0\text{e}6 \cdot (V - 28.6\text{V})$$

The 28.6V are the sum of the typical 27V break through voltage and the 1.6V offset of the SiPM-3000 input amplifier.

You can manually calibrate the detector, in which case you have more freedom on how to do it. If you want to use the (Calibrate) button on the (Histogram) panel, then the software will always pick the tallest peak in the histogram, beyond 50 MCA bins, to use in the calibration computations. This works best for isotopes with a well-separated medium-energy peak; eg Cs-137 and Na-22. Co-60 is not recommended for the software-assisted calibration.

4.3 Step 1 of the calibration

First, adjust the operating voltage to set the maximum measurable energy. Open the (fpga_ctrl) display and set the ha_mode control to 1. Start a new histogram acquisition on the (Histogram) display by clicking on (New). Wait until there are around 1000 counts in the peak maximum. Then click (Calibrate) on the (Histogram) display.

After 1 second, you will receive a message with the suggested new operating voltage. The software has applied the new operating voltage already if ***auto_update*** is set to 1.

There is some variation between the SiPM or PMT and you may have to repeat a second time to achieve the desired accuracy. Note that even if you do not know the exact gain exponent of your PMT, the process will still converge. It may just take another iteration or two.

Here is how to compute the ***cal_pulse_height (cph)*** :

$$cph = 900 \cdot \frac{\text{cal\_energy}}{E_{\max}}$$

4.4 Step 2 of the calibration

Now change the digital gain to achieve the desired MCA calibration in keV per MCA bin. From here on, the operating voltage and the electronic gain ***gain_select*** should be kept constant. Instead we use the ***digital_gain*** from the (fpga_ctrl) display.

Set the ha_mode control to 0 to return to normal energy measurements, and start a new histogram acquisition. Wait for sufficient accuracy and click (Calibrate) .

This time, you will receive a notice of the new ***digital_gain*** .

The new value was computed from a linear formula

$$dg_{\text{new}} = dg \cdot \frac{\text{cal\_energy}}{E_{\text{peak}}}$$

and it will be accurate on the first try.

However, keep in mind that there is a statistical uncertainty in determining the actual energy of the histogram peak. You can compute the 1-σ error from the fwhm (in %) and the number of net counts (N) above background in the peak as

$$\varepsilon = \frac{\text{fwhm}}{2.3655 \cdot \sqrt{N}}$$

5. Gain Stabilization

All MCA-3000 offer gain stabilization that keeps the gain, the trigger threshold and the maximum measurable energy constant. NaI(Tl) is the most commonly used scintillator, and it also one of the most challenging. Its brightness and pulse shape change with temperature, while the application engineer wants to keep constant not only the MCA gain (keV per bin) but also the trigger threshold and maximum measurable energy that is independent of temperature.

All MCA-3000 offer a user-programmable set of lookup tables to change the operating voltage and the digital gain to achieve this goal. In addition, for NaI(Tl) the MCA also vary the hold-off time with temperature to avoid retriggering on the tail end of the same pulse.

Since code and data needed for the gain stabilization are embedded in the MCA, no user software is required and the calibration moves with the detector.

The PMT-3000 also offers LED-based gain stabilization to counter PMT aging. Vacuum photomultiplier tubes lose gain over time, even under light to moderate loads. For example the popular R6231 PMT loses half its gain after an accumulated anode charge of about 50C. Distributed over one year, this equivalent to an average anode current of just 1.6µA, with a 6% gain loss per month. With a built-in LED that injects light into the back of the photomultiplier, the PMT-3000 can gain-stabilize on the LED response and counteract the PMT aging.

5.1 General theory of operation

All types of gain stabilization use lookup tables, and users can supply their own. The standard code includes a 64-long float array with three look up tables **(LUT)**. The MCA frequently determines the temperature and adjust the operating parameters according to the values found in the lookup tables.

The LUT depend on the scintillator and on one DSP setting, namely the integration time. For NaI(Tl) the LUT supplied by the factory use an integration time of 1.2µs. For the PMT-3000 and NaI(Tl) the LUT supplied by the factory was derived for an integration time of 1.2µs. That value remains fixed over the entire temperature range, as it provides the best energy resolution for small and large energies at all temperatures. For the SiPM-3000 and NaI we suggest a fixed integration time of 1.5µs.

But the hold-off time has to be varied. NaI(Tl) pulses become very long when the crystal temperature falls below 0°C. Consequently, the hold-off time has to be increased at low temperatures to avoid retriggering on the tail end of the same pulse. Since this phenomenon is determined by the scintillator physics, it has been implemented as an immutable function in the MCA, instead of a lookup table. The function is used if arm_ctrl["fields"]["cal_scint"]==1.

The implemented hold-off vs time function for NaI(Tl) is

$$\max(1.25, (0.634 + 1.27 \cdot \exp(-T/32.26)))$$

in µs and with T being the temperature in °C.

How the LUT are constructed. Developers may find that they need to construct the correct LUT for their detectors, as they may use a different scintillator or a different PMT. To this end the detectors needs to be run through a temperature cycle. The detector is recalibrated to desired specification at each temperature and the operating voltage, digital gain and possibly the LED value are recorded. Using interpolation one then constructs the LUT at the fixed temperature steps.

Keep in mind that many crystals don't allow for rapid temperature changes or they will crack. 10°C per hour is a safe bet for a 50mm NaI.

Secondly, it takes a while for a detector to attain steady state. The vacuum PMT needs an hour and the crystal characteristic time depends on the material and the size. For a 50mm NaI it takes about half an hour, for a 76mm NaI it takes 1.5hrs. Hence, it is necessary for a precise measurement, to maintain the detector at a fixed temperature for 2 to 4 hours before moving to the next.

Thermal equilibrium is necessary. Keep in mind that the PMT and the scintillator both have different temperature coefficients. If the two are not in equilibrium, there is no easy way to provide gain stabilization. Hence an outdoor

detector should be packaged with good thermal insulation to achieve thermal time constants of 2 hours or more – to ensure that all components are in a steady state situation. However, care must be taken not to insulate the electronics. Even if it only dissipates 300mW, that small amount of power stills needs to drain away to avoid self heating.

When using SiPM: SiPM-based systems react more quickly, because the SiPM-array has very little thermal mass. In uncooled systems its temperature may be close to the crystal or halfway between the electronics temperature and the crystal temperature, depending on the assembly.

In cooled systems the SiPM-array is well insulated from the crystal and its temperature remains constant as long as the Peltier cooling loop remains in regulation.

As a result, insulation for SiPM-based systems needs to be, at the minimum, just good enough to avoid cracking the crystal through temperature shock.

arm_cal registers and fields	
Index: name	***Description***
0: lut_len	Number of entries in the LUT; default is 19, 2..19 are allowed
1: lut_tmin	Minimum temperature in the lookup table; Typically -30°C
2: lut_dt	Temperature step size in the lookup table; Typically 5°C
[3:22]: lut_ov	Change of operating voltage vs temperature
[23:42]: lut_dg	Change of digital gain vs temperature
[43:62]: lut_led	Change of LED target vs temperature
63: lut_mode	int(lut_mode)&0x1 → lock bit, set to 1 to prevent the user from reading the arm_cal data from the MCA.

The arm_cal registers and fields.

5.2 Gain stab. summary

Standard software recognizes these gain stabilization modes (gsm):

- 0 ⇒ Off; Use when calibrating a detector.
- 7 ⇒ Suspend; Keep all parameters as they are.
- 1 ⇒ Use temperature lookup for change of operating voltage and digital gain; adjust hold-off if required.
- 2 ⇒ Compare measured LED value to expected value and adjust operating voltage accordingly. Use LUT for digital gain and compute hold-off time as needed.

arm_ctrl for detector calibration		
Name	***gsm***	***Description***
cal_ov	0,1,2	Operating voltage when the detector was calibrated
cal_temp	1,2	Temperature (in deg C) at which the detector was calibrated
cal_dg	1,2	Digital gain when the detector was calibrated
cal_scint	1,2	Scintillator type; 1⇒ NaI(Tl), adjust hold-off time vs temperature.
cal_target	2	Target value for response to LED; used with gain_stab=2

The arm_ctrl registers and fields concerning detector calibration; The gsm column lists the gain stablization modes for which this parameter is used.

LUT needed for detector calibration		
Name	***gsm***	***Description***
lut_ov	1	Operating voltage
lut_dg	1,2	Digital gain
lut_led	2	LED average

The lookup tables (LUT) needed detector calibration; The gsm column lists the gain stabilization modes for a given LUT is used.

5.3 Gain stab. mode: gsm = 0

Off. Gain stabilization is turned off and the target operating voltage the MCA will set is the one requested in arm_ctrl["fields"]["cal_ov"].

5.4 Gain stab. mode: gsm = 7

Suspend. This is different from gsm=0. During gsm $\neq 0$ the gain stabilization algorithm may have changed the target operating voltage to a temperature dependent value that is different

from arm_ctrl["fields"]["cal_ov"]. Setting gsm=0 would revert to that original value, while gsm=7 will leave the value unchanged. The same applies to the digital gain and the hold-off setting.

5.5 Gain stab. mode: gsm = 1

This mode relies on just the look up tables and the measured temperature. It is implemented for all MCA-3000. The units ship with LUT determined for NaI(Tl) at an integration time of 1.25µs

5.6 Gain stab. mode: gsm = 2

This mode adjusts the voltage using an LED measurement It is only implemented for the PMT-3000 series. The units ship with LUT determined for NaI(Tl) at an integration time of 1.25µs

The driving circuit for the LED used in the gain stabilization is electronically temperature compensated, but the compensation is not perfect. Since also the scintillator brightness changes with temperature, the ratio of the LED value and the full energy peak from a gamma-ray will be temperature dependent. Hence, there needs to be a lookup table to tell by how much the LED target value needs to be shifted as the temperature changes, in order to keep a full-energy gamma-peak constant.

Use an LED when expecting PMT aging. The purpose of the LED is to counteract PMT aging. This applies mostly to remotely installed detectors where a frequent recalibration is not possible. Whenever a detector can be recalibrated monthly and only sees light to moderate loads (anode current < 1µA with round the clock operation), then an LED system is not required.

Since aging is not a concern for SiPM, the SiPM-3000 series does not offer an LED option.

Adjusting the LED. In the LED panel you will find the controls shown in the table below

LED controls	
Name	***Description***
Period	LED frequency = $2441\text{Hz}/(P+1)$
Width	Driver pulse width = $W \cdot 0.050\mu\text{s}$
Attenuate	Attenuation factor = $1/2^A$
On	0→ Off; 1→ On;
Select	0→ LED pulses are hidden; 1→ Only show LED in histogram and traces

The LED controls.

Manual vs algorithmic operation of the LED. When gain stabilization is off the user can set the LED frequency and pulse width. When the detector has been calibrated, read the LED value from the RR_10 field on the (fpga_status) display and enter it into the cal_target field on the (arm_ctrl) display.

Don't run the LED too fast. Keep in mind that the LED pulses also cause a load on the PMT which may reduce its gain slightly (1% to 5% worst case). Hence, keep the LED running at ≤ 100Hz (P>24) during calibration. The PMT-3000 will update the measured LED average every 1024 pulses. At a rate of 100Hz, it will take 10s between updates.

Keep the LED pulses short, especially for high count rates. When using Select=1, you can see the LED values histogrammed. Mostly they will fall into a narrow peak of with an "energy resolution" of 1% to 2% fwhm. At high input count rates from a source (> 20kHz) you will also see a small fraction of events classified as LED that are a pile up of an LED pulse with a gamma-ray. These are rare, but they do slightly affect the accuracy of the LED average measurement. Keeping the LED pulses short helps to suppress these unwanted events.

The LED pulse is shorter than the drive pulse. Not only is the LED light pulse about 0.9µs shorter than the drive pulse, the FPGA logic also begins measuring the LED light only 1.5µs after the drive pulse starts. Hence if you set the LED width W<30 you will see a measured LED average of zero.

Similarly, the FPGA stops measuring the LED light about 0.15µs before the pulse actually ends. These two measure ensure that the LED light intensity is only measured during the flat

top of the pulse where the behavior is most predictable.

Usually the pulse height is adjusted at the factory to about 200mV when the detector is calibrated to have a maximum energy range of 3.2MeV. This allows operation with a higher gain and a lower energy range of down to 1MeV max, while keeping the LED pulse within ADC range.

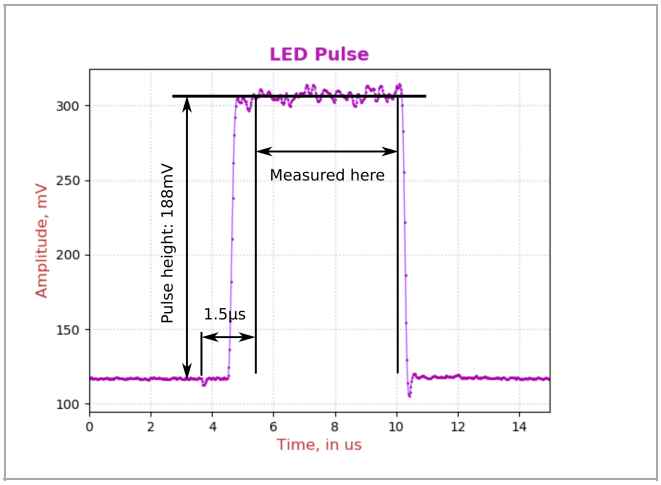
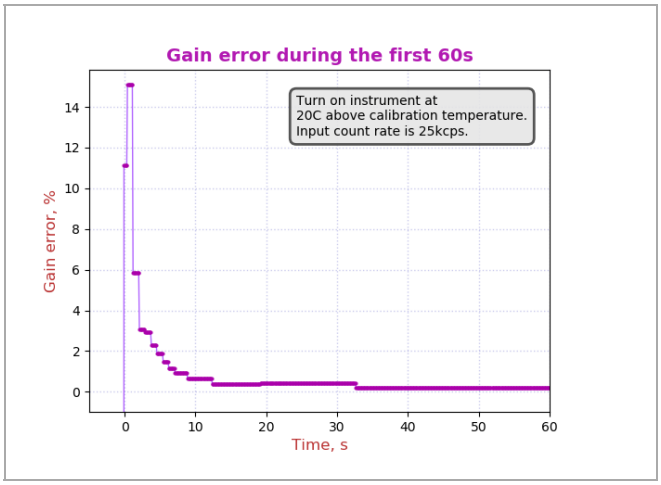


Fig. 5: A wide LED pulse to demonstrate how it is being measured.

5.7 Dynamical performance for gsm = 2

The gain error falls to < 1% in 10s. If an instrument that was calibrated at room temperature is left in a hot vehicle and turned on at a temperature much different from the calibration temperature, its initial gain settings will be all wrong for the new temperature. For gsm=1 the adjustment will be immediate, as the instrument only requires one temperature lookup to adjust to the new situation.

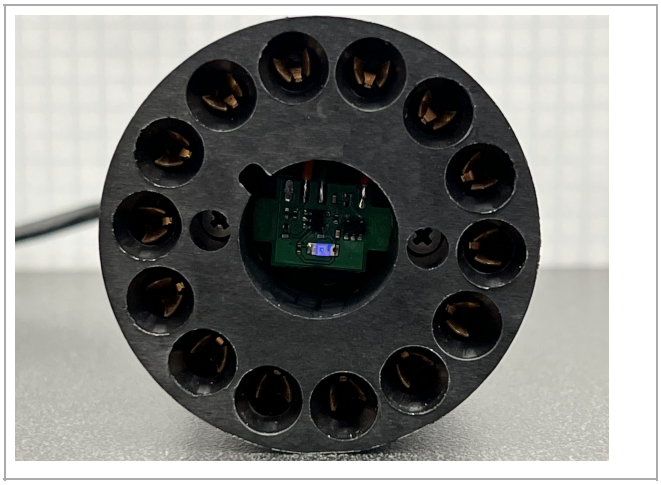
For LED-based gain stabilization (gsm=2) there is a short time lag. The instrument needs to measure the new LED value and then step by step adjust the high voltage to make the LED value meet the computed LED target. As shown in the figure below, this process takes less than 10 seconds. In the beginning the LED blinks at 1220Hz, and the high voltage is updated about every 0.8s. Once the LED value is close to the LED target (within 1%), the instrument gradually reduces the LED blinking frequency to 19Hz to reduce the load on the PMT and avoid accelerated PMT-aging.



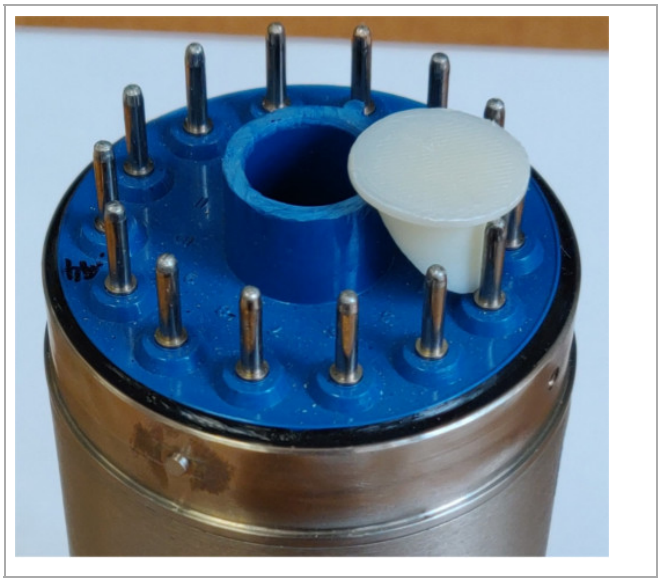
This is the response of the gain stabilization algorithm to turning on the detector at a temperature that is different by 20°C from the calibration temperature. Within 10 seconds the gain error falls back to below 1%.

5.8 Detectors and LED

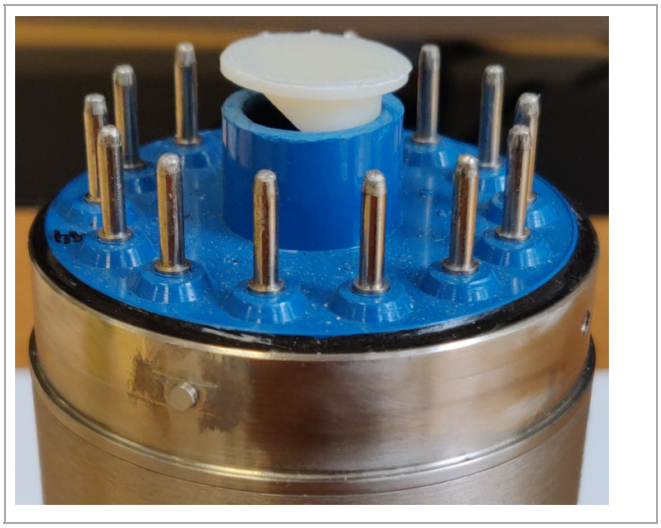
LED in the MCA not the detector: The PMT-3000 can be equipped with an LED for the purpose of gain stabilization. The LED is mounted on the underside of the high voltage unit. The LED shines its light through the back of the PMT.



View into a high voltage base with embedded blue LED.



Detector with an opening for the LED. The white light diffuser is shown on the side.



Here the white light diffuser is partially inserted.

Retrofitting is possible: Most detectors can be retrofitted to accept the LED light. Carefully cut open the back of the PMT socket. Once the MCA is plugged onto the PMT, the assembly is light tight again. In integral detectors the PMT is glued directly to the crystal and the environmental seal is usually between the side of the PMT and the magnetic shield. Hence, opening up the back of the PMT does not cause a problem.

Adjusting the diffuser: First keep the LED off and adjust the gain of the detector as desired. Then, insert the diffuser, turn the LED on, set `sel_led=1`, `trace_mode=0` and acquire a few traces. You will see a rectangular LED pulse with a width that can be controlled with the `led_width` control. For now we are only concerned about the pulse height.

In the MCA the LED is placed off-center and the light diffuser is asymmetric. Turning the light diffuser changes the amount of LED light transmitted into the PMT. You have to unplug the PMT-3000 from the PMT in order to turn the light diffuser. Note that you have to power down the MCA before plugging and unplugging. Never hot-plug the PMT-3000. It would damage the device.

Aim for LED pulses of around 200mV ±50mV, cf Fig. 5. Then glue the light diffuser into the opening. For precise operation, the diffuser must be securely glued in, otherwise it will change its position during temperature cycles.

6. Summation Weights

Normally the MCA-3000 measures a pulse energy by first subtracting the DC-baseline, and then by summing all ADC samples over an integration time. All ADC samples are weighed equally. But the MCA-3000 offers a more fine-tuned control: $E = \sum_k y_k \cdot w_k$

Improve the performance of certain scintillators. In some unusual scintillators the energy resolution can be improved if the summation weights w_k are not all equal. One example is SrI(Eu) where in big crystals the self-absorption of its own scintillation light can create significantly different pulse shapes for the same amount of energy deposited in the crystal; say for 662keV. The scintillator grower may have a recommendation, or the user can apply iterative or machine learning methods to find an optimized set of summation weights.

Most often, however, summation weights will be advantageously used to create powerful pulse shape discrimination algorithms as discussed in the section.

Within the FPGA, 1024 consecutive summation weights are stored, which covers integration times up to 8.53µs (@120MHz ADC speed) or up to 51.2µs (@20MHz ADC speed).

Ignore if not needed. By default all summation weights are set to 32767. For the purpose of energy measurement, the weights are considered to be unsigned 16-bit integers, with a range from 0 to 65535. Unless this feature is used, users can completely ignore this.

There is only one set of weights. When psd_on=0, the weights are treated as uint16_t and are used in the computation of the energy sum. When psd_on=1, the weights are used for the psd sum instead of the energy sum.

The software ships with a big examples section, where the user can find short python scripts to program custom weights into the FPGA, and even store them in the ARM processor's non-volatile memory.

7. Pulse Shape Discrimination

PSD is controlled by the user. Both MCA-3000 support a very general, patented, pulse shape discrimination method that gives the user great control. The user can define 16-bit signed weights to apply to each ADC sample in a pulse after triggering. $P = \sum_k y_k \cdot w_k$. For each event the firmware classifies the event as being type 0 or 1.

When PSD is turned on, the firmware separates type 0 and 1 events into two separate halves (2Kx32) of the available histogram memory. Type 0 events are always histogrammed in the lower half, while type-1 events are recorded in the upper half. For both types of events there is a separate event counter to measure count rates.

When PSD is turned on, the firmware separates type 0 and 1 events into two separate halves (2Kx32) of the available histogram memory. Type 0 events are always histogrammed in the lower half, while type-1 events are recorded in the upper half. For both types of events there is a separate event counter to measure count rates.

This feature is compatible with loss-less histogram acquisition where the histogram is split into two separate banks. In that case there will be four 1Kx32 spectra.

See wxMCA/examples on how to program the weights. Consult the examples folder of the software to find code examples that write summation weights to the FPGA of the MCA-3000 and to the non-volatile memory of the ARM processor.

Factory default: The factory default for the weights is 32767, which is very nearly the same as 1.0. When psd_on=0, the weights are used for regular energy measurements, and having all weights to be equal and near 1.0, is a reasonable default.

When psd_on=1, the weights are used for pulse shape discrimination (PSD). The default set will not provide any PSD, and the user must program a new set of weights. This is discussed in detail below.

7.1 Where does the pulse begin?

In order to select the weights it is helpful to see exactly where a pulse starts, ie to which ADC sample the first weight is applied. To this end set **psd_on=1** and **trace_mode=0**. Then acquire a set of 10 pulses.

You will notice that the pulse peaks all occur at the same time. The PMT-3000 issues its internal trigger when the signal reaches its peak. The weights summation starts at sample 0.

The distance between sample 0 and the pulse peak is 12, 24 and 36 samples for ADC speeds of 40MHz, 80MHz, and 120MHz, respectively.

7.2 A theoretical example

Here we consider a theoretical example to explain how the PSD feature works. In the next section we show a practical case.

Consider a phoswich detector in which beta-particles create short pulses, and gamma-rays create long pulses. Here we just consider a much simplified version using two triangular pules shapes. For simplicity, we also assume that the trigger point is exactly at the start of the rising edge.

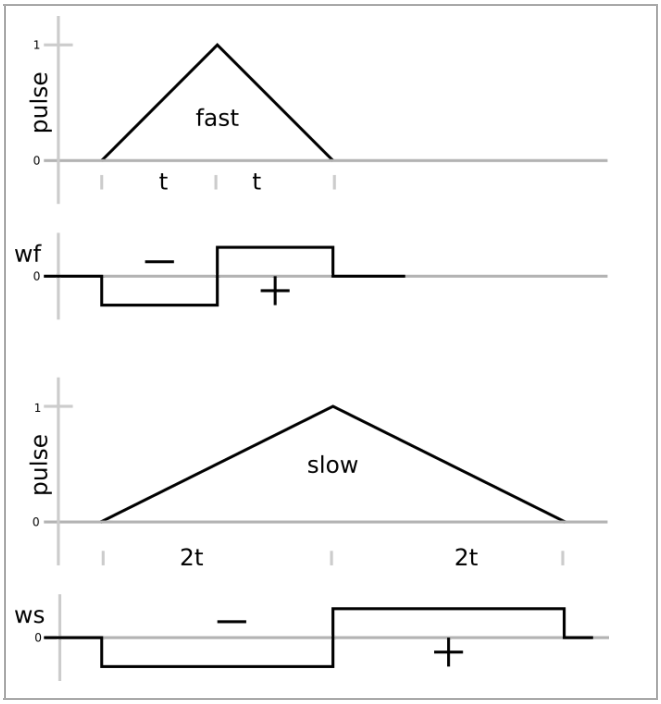


Fig. 6:Pulse shape discrimination using summation weights.

Consider applying the weights wf to the fast pulse. Because of the symmetry, the sum will be zero. But the same wf weights applied to the slow pulse will create P>0.

Similarly, applying the weights ws to the slow pulse will result in P=0. But the same ws weights applied to the fast pulse will create P<0.

Hence, using a weight function that is between wf and ws will map fast pulses to P<0 and slow pulse to P≥0. The firmware uses 0 as the decision point.

7.3 Weights format

Weights are signed 16-bit integers. When pulse shape discrimination is turned on, the weights are used as indicated in table 3. Since most of the control and GUI software treats the FPGA controls, and the summation weights as unsigned 16-bit, consult the table below to correctly encode the weights values.

PSD Weight	*uint16_t value*
-1	32768, 0x8000
-0.5	49152, 0xC000
-0.25	57344, 0xE000
0	0, 0x0
0.25	8192, 0x2000
0.5	16384, 0x4000
1-1/32768	32767, 0x7FFF

Table 3: Encoding PSD weights as 2's complement unsigned int 16. The largest possible positive value is represented by 0x7FFF=32767. The most negative possible value is represented by 32786=0x8000.

7.4 PSD controls

Set `psd_on=1` to turn on pulse shape discrimination. Set `psd_sel=1` to histogram the PSD sums used for the decision making, instead of histgramming event energies.

You can control which type of pulse is histogrammed in the low-bins of the histogram memory. If weights start with a block of negative values the condition P<0 will select fast events and these will be histogrammed in the lower part of the histogram memory. A user can reverse this by changing the sign of all weights. Now, P<0 will select the slow pulses and the slow pulses will be histogrammed in the lower part of the memory.

Fast pulse and slow pulse count rates are measured separately. The firmware uses two extra sets of event counters. XCTR_0 counts pulses for which P<0. XCTR_1 counts pulses for which P≥0. Both extra counters and their associated count rates are reported by the MCA Data Server and are displayed in the GUI.

Note that XCTR_0 and XCTR_1 also accept pulses arriving at their designated GPIO pins. Feeding counting pulses into the GPIO pins of XCTR_0 or XCTR_1 while using pulse shape discrimination will lead to erroneous results.

7.5 PMT-3000 β/γ Example

For precision spectroscopy, the PMT-3000 slows down the scintillator pulses. When using a β/γ phoswich made of a plastic scintillator and a NaI-detector, the plastic scintillator pulse is much faster than the NaI

light pulse, which makes pulse shape discrimination an easy task in this case. However, the user may decide to use a bigger electronic gain to keep the PMT gain low and reduce aging effects – while also using a 40MHz ADC for lowest power consumption. Below we show the performance of such a PVT/NaI phoswich detector.

Even small pulse shape differences can be used. The phoswich was constructed using a 50mm×50mm NaI(Tl) crystal and a 3mm plastic scintillator (PVT). The PMT-3000, operating at 40MHz, was set to use the 3400 Ω gain setting to purposefully slow down the electronic pulses.

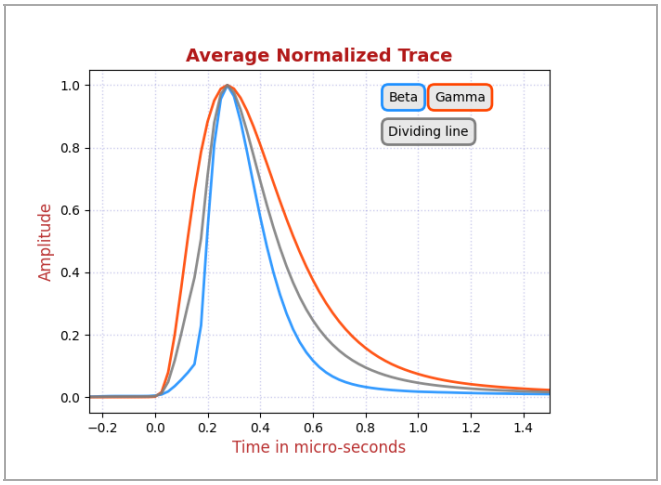


Fig. 7: Average of 10000 beta and gamma traces, acquired on a PMT-3000 at 40MHz digitization rate with a PVT/NaI phoswich detector.

Observe in fig. 7 how the β-pulses (blue) are on average slightly faster than the γ-pulses (red). Their pulse width (fwhm) is about 250ns vs 500ns for the γ-pulses from the NaI. The difference is clearly visible, but not very pronounced. The grey pulse is the arithmetic average between the two, and we will use it to create the PSD filter.

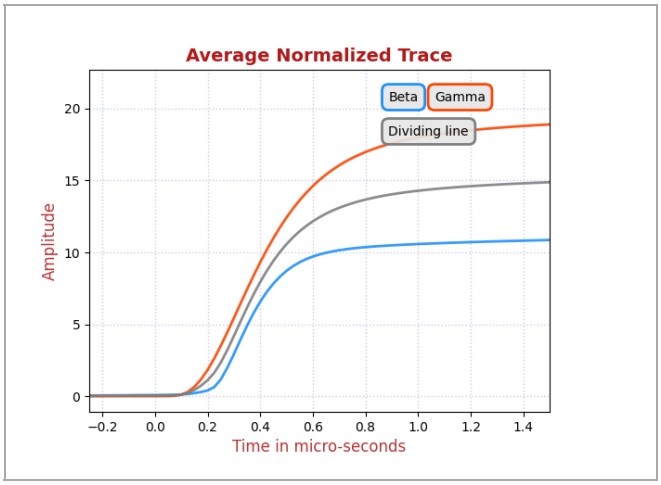


Fig. 8: Average of 10000 beta and gamma traces, after integrating the pulses starting at 0.

Observe in fig. 8 how the integrals of β-pulses (blue) and γ-pulses (red) diverge strongly from each other beyond 0.5μs. At 1.0μs the integrals are markedly different for pulses that have the same maximum pulse height. Using energy integrals E_0 and E_1, one can build a first PSD equation $P = E_1 - r \cdot E_0$. We want to choose r such that the dividing line shown in grey would map to zero $P = 0$. With that choice we expect $P(\beta) < 0$ and $P(\gamma) > 0$.

In this example, we find that on the dividing line, $E_0 = 10.6$ and $E_1 = 14.3$, hence we select $r = 1.351$ in order to map the dividing line to 0.

In the MCA-3000 the pulse integral is approximated by sums over ADC samples. For a 40MHz ADC, 0.50μs means 20 ADC samples.

$E_0 = \sum_0^{19} y_k$ and $E_1 = \sum_{20}^{39} y_k$

We can write the PSD sum $P = E_1 - r \cdot E_0$ as $P = \sum_0^{39} w_k y_k$, which here simply becomes $P = (1 - r) \sum_0^{19} y_k + \sum_{20}^{39} y_k$

We show this first iteration of the summation weights w_k in fig. 9

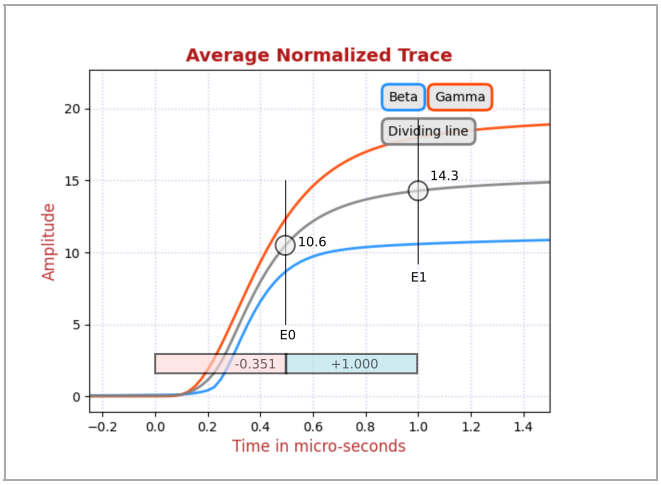


Fig. 9: Average of 10000 integrated beta and gamma traces, now shown with a first estimate of PSD summation weights.

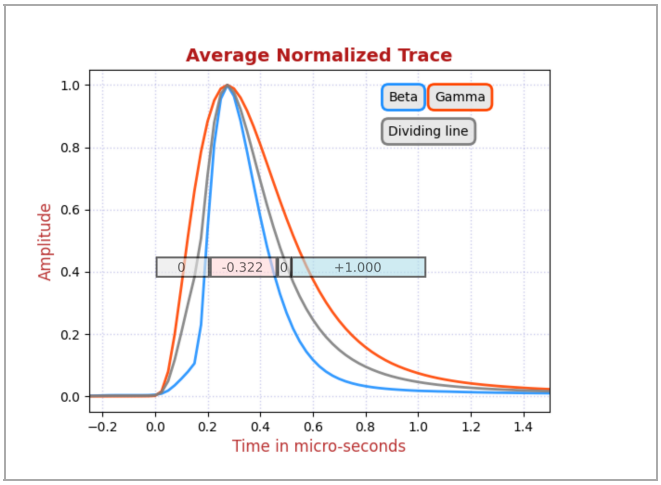


Fig. 10: Average of 10000 integrated beta and gamma traces, now shown with a tuned set of PSD summation weights.

In practice, one finds that the performance can be improved if the summation focuses on those ADC samples where the signal to noise ratio is big. For example, focusing the PSD sum E_0 on those times where both the β- and the γ-pulses are significantly greater than 0, helps to avoid adding just noise to the sum without accumulating meaningful information.

The MCA-3000 lets a developer tweak the PSD summation weights to achieve the best performance. In fig. 8 we show the result of a practical tuning for the above-described PVT/NaI phoswich. In this case, we had adjusted the gain such that the maximum measurable energy would be 1.6MeV and the NaI-trigger threshold was set to 50keV. The reasoning was that low-energy γ-rays (eg 30keV from Cs-137) will often be stopped in the 3mm-thick plastic scintillator. This would lead to many false beta counts, not because of limits of MCA pulse shape analysis capabilities, but because of the physics of γ-rays.

Inspecting fig. 10 shows the strength of the approach. Instead of just comparing complete energy sums, we can create partial sums at will, as every weight w_k can be set individually.

The MCA-3000 provides a tool for the developer to judge the performance of the pulse shape discrimination. In the fpga_controls set **psd_on=1** and **psd_sel=1**. In the **(Histogram)** panel set the number of MCA bins to 4096, to see the entire spectrum. Keep in mind the PSD decision sums are centered around bin 2048 in this display.

With these settings you will see a 4K histogram of the PSD sums. Events to the left of bin 2048 will fall in one class, and events in bins ≥ 2048 will fall into the other. The shape of the PSD histogram on either side of the divide is not of much interest. The only thing that counts is that the right and left side of the spectrum are separated by a clear gap.

Fig. 11 below shows an example. This one was acquired using a weak Tl-204 source encapsulated in 2mm of plastic in the presence of natural γ background. In the PSD histogram you can clearly see the two classes of events, well separated by a gap around zero (ie the middle of the 4K histogram).

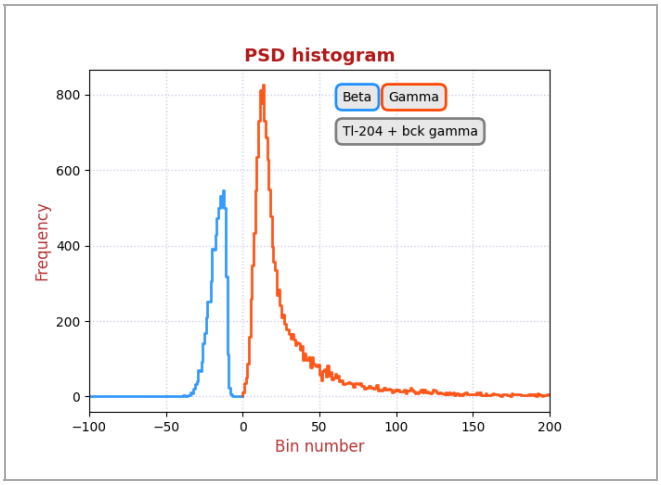


Fig. 11: Pulse shape discrimination (PSD) histogram for Tl-204 and background γ's using the PVT/NaI detector + PMT-3000 and settings as described above. Here we set bin 2048 as 0 for clarity.

7.6 SiPM-3000 Example

In the SiPM-3000 PSD is limited to time >150ns. In an SiPM-3000 the large capacitance of a 3.4cm^2 SiPM-array lengthens the pulse width at the output of the input amplifier. At the same time, the recharge time of a Broadcom S4N66 SiPM is 150ns. Hence, pulse shape discrimination is limited to times greater than 150ns. Below we show that a PVT/NaI phoswich detector will still perform well.

The fast scintillator can be much faster than 150ns. The phoswich was constructed using a 50mm×50mm NaI(Tl) crystal and a 3mm plastic scintillator (PVT). The light pulse from the PVT is only a few ns wide, but the SiPM-array lengthens that to the recharge time of 150ns. On top of that, the input amplifier is slowed down by the large capacitance of the SiPM-array. As a result, we see the two normalized and averaged pulse shapes; fast for beta-particles being stopped in the PVT and slow for gamma-rays interacting in the NaI.

Construction of the β/γ phoswich: The SiPM-array is coupled to a dual-window NaI-assembly. The SiPM-side is called the top. Away from the SiPM, at the bottom, a plastic scintillator is mounted against the NaI-assembly. The plastic scintillator is at the bottom side.

Construction of the summation weights: Using summation weigthts is a very general method to achieve pulse shape discrimination. One way to arrive at a first useful set of summation weights is to consider those regions where the two types of traces are similar, and where they are different.

In this case we apply a negative weight to the region where the two traces are almost the same. In the regions where the γ-ray pulse values (from the NaI) are significantly bigger than the blue β-pulse values, we apply a positive weight. The value of the positive weights is adjusted such that all βs map to <0 in the PSD histogram, and all γs map to >0 in the PSD histogram.

The weights can then be varied to optimize the PSD performance. Below we show the result for the same PVT/NaI phoswich, but here used with the SiPM-array instead of a PMT.

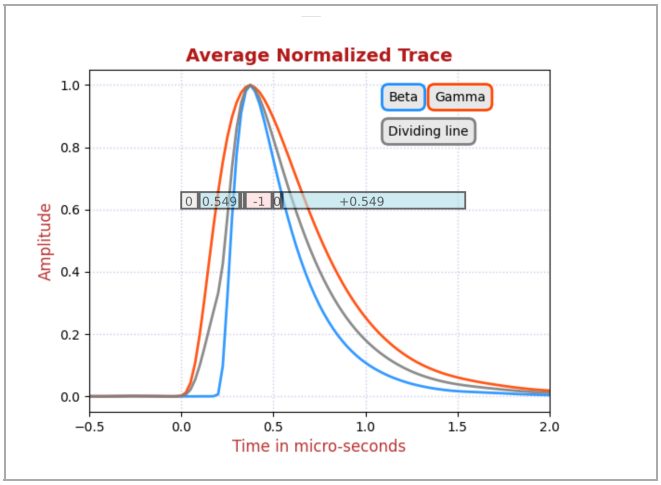


Fig. 12: Average of 10000 beta and gamma traces. In addition we show the summation weights used to obtain good β/γ separation.

PSD histogram An example β/γ PSD histogram is shown in figure 13. Even with the limited speed of the input amplifier in an SiPM-3000, the beta/gamma separation is nearly perfect.

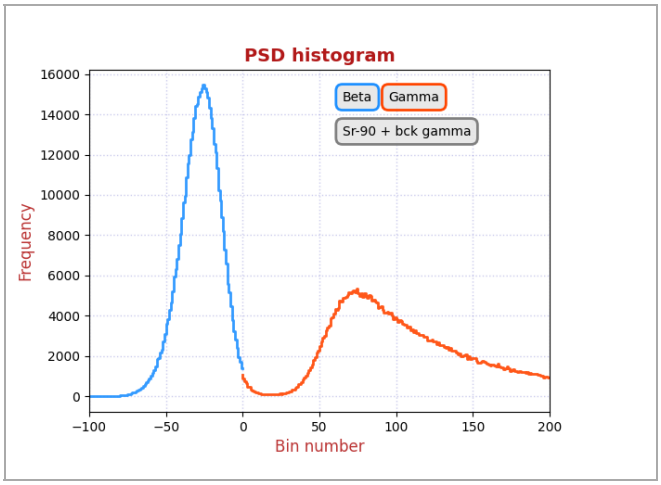


Fig. 13: PSD histogram for the combination of a weak Sr-90 source with a count rate equal to background γ's.

Item	*Performance*
Sr-90	If detected, 95% are classified correctly.
Cs-137	<0.005% false betas; with Cs-137 above the NaI top side.
Background	~0.2cps β
Settings	Max γ-energy: 3.2MeV; trigger threshold at 50keV.

Table : Performance of the SiPM β/γ phoswich.

8. Software upgrades

Upgrading and updating software: The MCA-3000 ARM code can be upgraded or updated in the field via its USB connection. This feature allows to deploy code with bug fixes (updates) as well as the delivery of completely new custom software with application specific features and capabilities. All files are fully encrypted. They can be delivered to the developer, and even to the enduser customer without compromising software security. Once loaded into the MCA, the software can not be read back.

8.1 ARM code upgrade

Using the bootloader: When the user receives a new ARM executable, as an encrypted file, they can load that file using the boot loader. This is a two-step process.

Step 1 Invalidate App: Using the examples in the examples/software_update folder, first invalidate the running application by executing the invalidate_app.py file. This sets a bit in non-volatile memory. Then power cycle the device or force a CPU restart (arm_restart.py)

Step 2 Uploading code: After the ARM CPU reboots, the MCA will be recognized by the computer's operating system as a USB device with Bridgeport's vendor ID, but now with a new product ID, namely PID=0x1000. Close the MCA Data Server.

On Windows: If you are performing the procedure for the first time on a Windows machine and are using libusb0.1, you must run wxMCA/zadig.exe and install libusb_win32 as the device driver. From then on Windows will remember the driver for this new device. On Linux no action is necessary.

Relaunch MDS: Launch the MCA Data Server again. It will now report a PID of 0x1000, and it will report the same serial number that the MCA already had when shipped. The serial number does not change in the process.

Uploading code: Copy the encrypted arm executable to the software_update/data folder. Edit the file name in the manage_arm_code.py file and execute that file. A typical code is uploaded in 10 seconds, but the maximum time for the biggest possible code size is 80 seconds.

Relaunch MDS: After the code has been uploaded, the computer will register a disconnect and reconnect series of events on the USB bus. This happens because the updated application relaunches the USB interface. Exit the MDS and launch the MCA Data Server again. It will now report a PID of the MCA, and the same serial number as before.

Step 3 Validate App: Test the new application to make sure it works, then validate the application. Execute the accept_app.py file. It issues a command to clear the invalid/valid bit. With that done, the internal bootloader will

automatically boot into the application after the next power cycle.

Risks: There is no risk to permanently disable the device. When BPI distributes an update, BPI will also distribute a safe fall back code. If for some reason the processor fails to boot into the application after the code update, simply power cycle the device. Since its program memory has ben declared invalid, the boot loader will simply wait for the next attempt to upload code via USB.

9. Analog

9.1 PMT-3000

The PMT-3000 combines a PMT operating voltage supply and an MCA data acquisition board with a structure as shown in the figure below.

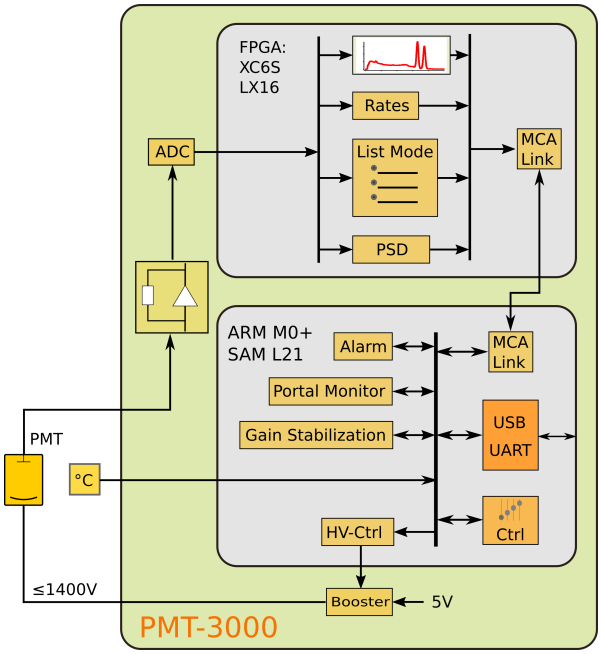


Fig. 14: The components of the PMT-3000.

The analog input of the PMT-3000 uses an I-to-V converter with four programmable gain resistors as shown in the figure below. A gain_select of 0, 1, 2, 4, and 8 creates a transimpedance of 100Ω, 430Ω, 1100Ω, 3400Ω, and 10100Ω, respectively.

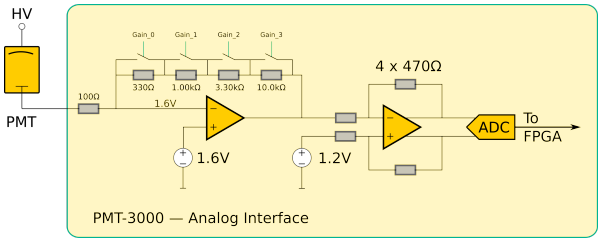


Fig. 15: The input amplifier of the PMT-3000.

9.2 SiPM-3000

The SiPM-3000 combines a very low-noise SiPM operating voltage supply and an MCA data acquisition board with a structure as shown in the figure below.

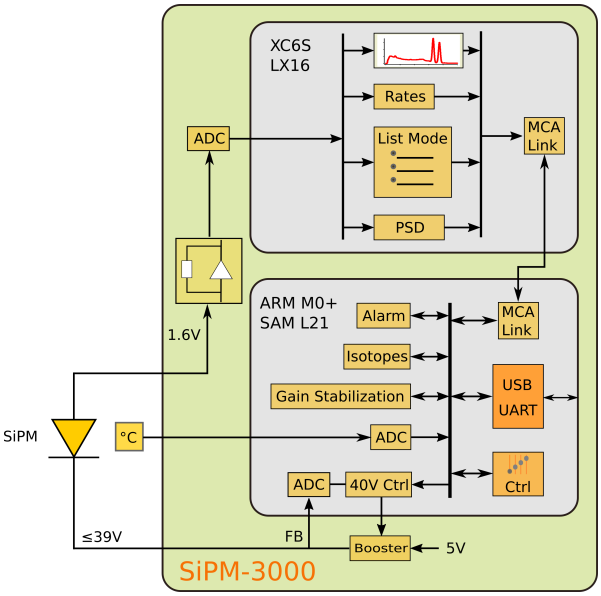


Fig. 16: The components of the SiPM-3000.

The analog input of the SiPM-3000 uses an I-to-V converter with four programmable gain resistors as shown in the figure below. A gain_select of 0, 1, 2, 4, and 8 creates a transimpedance of 5Ω, 20Ω, 55Ω, 155Ω, and 505Ω, respectively.

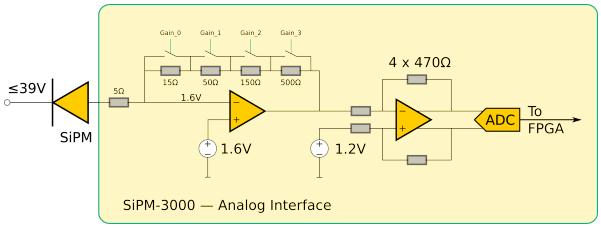


Fig. 17: The input amplifier of the SiPM-3000.

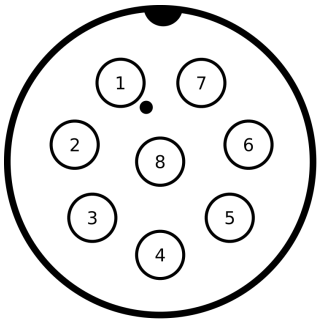
10. Mechanical and Pin Outs

10.1 8-Pin Connector

The PMT-3000 uses a Bulgin PX0447 mini-B USB connector for power and USB

communication. Mating cables are the Bulgin PX0441 (USB-A) and PX0442 (USB mini-A) series cables. They come in lengths from 2m to 4.5m.

The PMT-3000 uses a Switchcraft EN3P8MPX 8-pin connector for GPIO and serial UART communication. The mating connector is part of the EN3C8 series.



PINOUT

No.	SEL=0	SEL=3.3V
1	TMS	S0
2	TDO	S2
3	TDI	S4
4	TCK	S6
5	Vref	S7
6	VD50	VD50
7	GND	GND
8	SEL	SEL

SEL=0: JTAG to FPGA
SEL=1: FPGA GPIO

Fig. 18: Pinout of the EN3P8 connector.

11. Product and Part Numbers

11.1 Product numbers

The PMT-3000 is part of a product series that all contain an ARM M0+ 32-bit processor for communication and slow control, such as gain stabilization. In the -1000 series the MCA is implemented by software in the ARM processor. In the -3000 series the MCA is implemented independently within an FPGA for very high-speed operation. The -3000 series also uses a waveform-digitizing ADC and offers detailed pulse capture and real time pulse shape discrimination.

Both types of devices are available for vacuum photomultiplier tubes (PMT) and Si-photomultipliers (SiPM). In both cases, the device generates the operating voltage for the photo-sensor from the incoming 5V.

P/N	*Sensor*	*FPGA*
PMT-3000	PMT	Yes
SiPM-3000	SiPM	Yes

Table : Part numbers.

11.2 USB-ID

On the USB bus devices are recognized by their Vendor ID (VID), Product ID (PID) and Serial Number (SN). The vendor ID for Bridgeport Instruments is 0x1FA4. The Product ID's are shown in the table below. Within a product the serial number is fixed, unless BPI makes a custom device that requires a non-standard driver. Note that simple extensions, such as adding a variable to the controls, does not require a new driver.

The BPI software recognizes individual devices by the unique serial number burnt into each ARM processor. The device reports that when the host reads **arm_version**. The serial number communicated in response to USB setup commands is fixed for each part, to avoid that the host keeps adding every new device to an ever longer list of devices requiring a designated USB driver.

P/N	*PID*	*SN*
PMT-3000	0x0103	armMorpho0001
SiPM-3000	0x0203	sipmMorpho0001

Table : Product ID and USB bus serial numbers. The vendor ID is always VID=0x1FA4.

11.3 Device serial numbers

Each ARM processor has an immutable 128-bit unique serial number, which can be printed as a 32-character hexadecimal string. The MCA Data Server always uses the complete 32-character string to identify the device. Because of space constraints, the serial number printed onto the device is shortened to 8 hexadecimal characters.