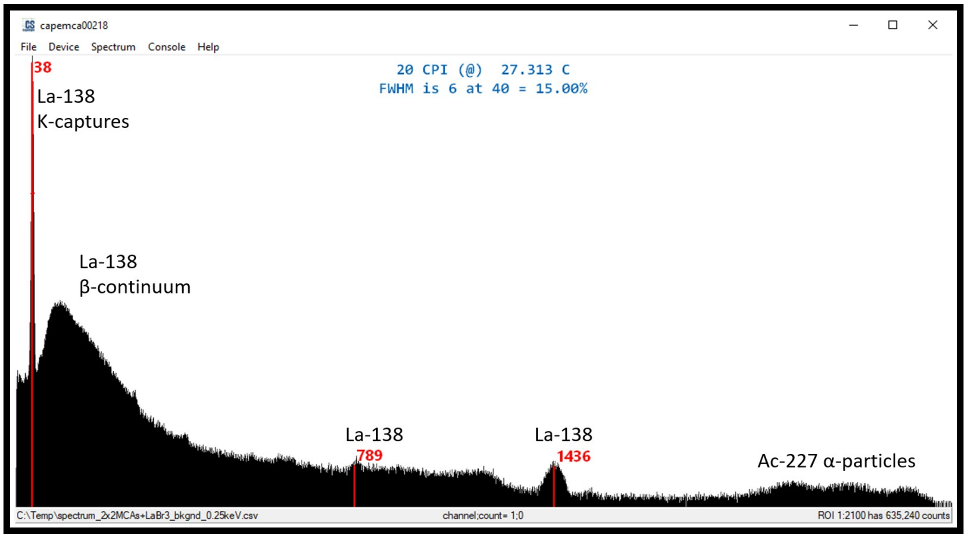
CapeMCA™ 1.4.1a Users Manual

A Real-Time Gamma Energy Spectrum Monitor for CapeSym's STM32-Based USB Multi-Channel Analyzers



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Versions and Compatibility

The CapeMCA software, which runs on the Microsoft Windows x64 desktop operating system, is used to request data from CapeSym's MCA hardware via the USB 2.0 interface. A 32-bit version is also available to support Windows for ARM tablets and other platforms that can use Win32 emulation. In this document, the Windows computer will often be called the *host* or *PC,* with the CapeMCA application referred to as the *host software*. The code that runs on the MCA hardware is called *firmware*. Host software and firmware have different version numbers, that are distinct from the hardware versions (see Table 0 and Figure 1).

Table 0: Latest firmware versions and features, along with compatible version of PC software

Hardware Version	Latest Firmware	Firmware Update	PC Version	Firmware Features								
				DPP	**Spectra Types**	**ADC**	**Msps**	**Clock**	**PS**	**WR**	**TC**	**1IT**
1.0.59b	1.3.9	4-28-2025	1.3.8	□+integral	E,W,S,L,T	14bit	10	2ppm	no	yes	no	yes
1.0.62	1.1.13	9-17-2024	1.3.8	□+integral	E,W,S,L,T	14bit	5.00	1%	no	no	no	no
1.1.18	1.2.0	7-05-2023	1.3.2	□+integral	E,W,S	12bit	5.56	1%	no	no	no	no
1.0.75	1.3.9	4-28-2025	1.3.8	□+integral	E,W,S,L,T	14bit	5/10	1%	no	yes	no	yes
1.5.7	1.3.9	4-28-2025	1.3.8	□+integral	E,W,S,L,T	14bit	5/10	1%	no	yes	no	yes
1.2.1	1.4.2	10-01-2024	1.3.9	Δ+decay	E,W,S,L,T,I	14bit	10	25ppm	no	yes	yes	yes
1.7.21	1.4.7	04-23-2024	1.4.0	Δ+decay	E,W,S,L,T,I	14bit	5/10	25ppm	yes	yes	yes	yes
1.8.23	1.4.4	1-31-2025	1.3.9	Δ+decay	E,W,S,L,T,I	14bit	5/10	25ppm	no	yes	yes	yes

DPP: digital pulse processing: **□+integral:** box filter detection & pulse integration, **Δ+decay:** triangular filter with decay compensation, Available spectra types include **E:** energy, **W:** pulse width, **S:** pulse sample, **L:** pulse list, **T:** test pattern, **I:** interarrival interval distribution
ADC: analog-to-digital converter resolution, **Msps:** millions of samples/s, **Clock:** frequency stability, **PS**: Peak servo of DAC vs. temperature, **WR:** watchdog reset option, **TC:** true count correction; **1IT:** interarrival timer for first pulse in a pulse list

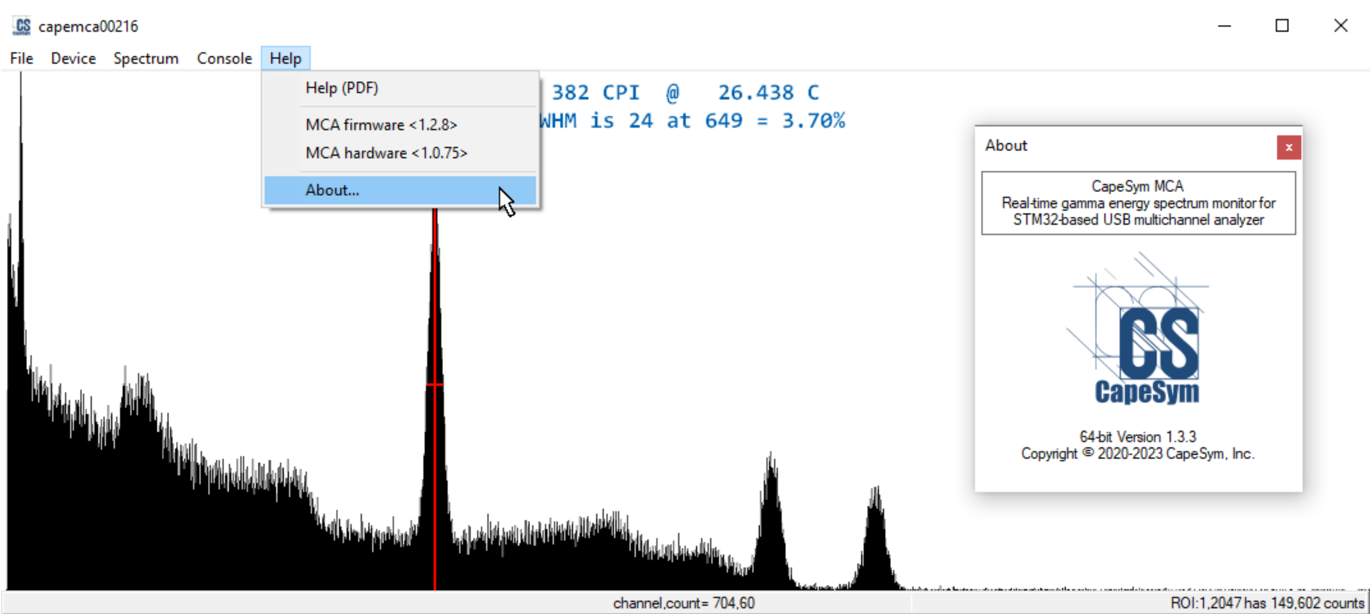


Figure 1: The version number of the Windows software is shown in the About dialog, while the version numbers of the firmware and hardware are shown in the Help menu after connecting to the MCA device via the Device menu.

Windows Application

CapeMCA is the real-time gamma energy spectrum monitor for CapeSym's Universal Serial Bus (USB) multichannel analyzers (MCAs). These MCAs are designed to operate continuously, processing pulses and accumulating gamma spectra, pausing only briefly at low frequency of (0.1-10Hz) to check for information requests from the host computer. The MCAs are fully self-contained, generating the bias voltage for silicon photomultipliers (SiPMs) arrays, and automatically adjusting the bias to compensate for the temperature-dependence of the SiPM breakdown voltage and response amplitude.

Turn on the MCA device by connecting it to a Windows host computer using a USB cable with a *microB* connector. Windows 10 or higher will automatically recognize the device and setup the USB driver. See Appendix A for more information on USB drivers for older Windows versions or other platforms.

During power-on initialization, a yellow or blue LED on the MCA will illuminate. This LED will turn off within a second or two, signaling the end of initialization and the onset of radiation detection. The MCA accumulates a radiation energy spectrum and then pauses to check whether the host has requested that the spectrum be sent via USB. If so, the spectrum is transferred to the CapeMCA host application while the MCA returns to pulse processing. Pulse processing continues until the next communication interval. At each pause for communication, the MCA turns on the green LED (whether or not data is transferred), and then turns it off again when pulse processing continues.

When the MCA is functioning properly at power-up, a yellow or blue LED will appear briefly followed by the green LED blinking periodically (Table 1). The blink may be very faint when no spectrum is transferred to the host. The blinking frequency is determined by a parameter in the MCA firmware, which is usually set to 1 Hz at the factory. The MCA is powered by the USB 5V supply, so if no LEDs are visible, check the USB cable connection. LED timings and colors may differ between hardware/firmware versions.

Table 1: LED Indication of MCA Status

LED Color[1]	Duration/Freq	MCA State
🟡 Yellow/blue	~0.5 s	Immediately following power-on or soft reset
🟢 Green/red	Up to 3.5 s	USB host and array communications detection
🟡 Yellow/blue	~0.25 s	Start up from stop, during HV stabilization
🟢 Green blink	0.1-10 Hz	MCA running, communication phase
🔴 Red	continuous	MCA not running, awaiting host instruction
🟡 Yellow/red blink	0.1-10 Hz	MCA in array is running but not synchronized
✖ Off	0.1-10 s	MCA running, data acquisition phase
✖ Off	continuous	Bootloader is running, power-on reset required

[1]Some hardware versions use blue in place of yellow.

Proper operation of the MCA requires that a detector module is also connected. ***The detector module should remain connected to the MCA at all times*** while the MCA is powered. Connecting the detector module after the MCA is already powered will produce erroneous readings from the sensor due to the fact that the detector was not present throughout the initialization period. In some instruments, the detector module attachment to the MCA is permanent. Attempting to detach the detector from the MCA in such cases will destroy the instrument, even when USB power is not connected.

Establishing USB Communications

Start the CapeMCA application. Establish USB communications with the MCA hardware by selecting the *Connect* item from the Device menu. If multiple MCA devices are connected to the computer a dialog will appear allowing selection of one of the MCAs. Details about the success or failure of the USB device connection are then reported to the console. Multiple tries at establishing a connection may be required under some circumstances.

The spectrum will be displayed a few seconds after establishing the USB connection. This delay depends on the communication interval setting in the MCA firmware. After a brief delay, the CPI (Counts Per Interval) text at the top of the window should begin updating at every communication interval. If no updates are being reported, try selecting *Disconnect* from the Device menu, and then try *Connect* again. If updates still fail to appear in the GUI, try unplugging the microB connector from MCA hardware and plugging it back in, then retry Device > *Connect*. Sometimes the LEDs on the MCA may indicate 5V power connection even though the USB data lines are not fully engaged. This might be true if the connector is not inserted all the way, or if a USB charger or charging cable is used that does not have data lines.

Do not allow the force of plugging or unplugging the USB cable to be transmitted to the detector. Stress on the detector module could damage its seal causing signal degradation due to air and light exposure.

If the spectrum still does not appear, verify that an LED turns on when the USB cable is first plugged in. If the green LED does not start blinking, it is possible that the MCA communication interval was set to such a large value that MCA will not attempt to communicate with the host for a several seconds. In this situation it will be necessary to wait for multiple communication intervals in order to stop the MCA and restore factory settings, because host commands are processed at a rate of only one command per communication interval. If the green LED is blinking, but no spectrum appears in the main window, then either there are problems with the parameter settings or the detector has been damaged.

When a connection is established to the MCA hardware, the *Disconnect* menu item becomes available in the Device menu. The *Disconnect* item will break the USB communication link without disrupting the behavior of the MCA hardware. As long as the hardware remains plugged in to the USB power source, it will continue to accumulate a spectrum according to the current settings. The user may then use *Connect* to re-establish the communication link and retrieve the accumulated data. The USB cable may be unplugged without first using the *Disconnect* menu item. Physical disconnection is detected by the PC software.

Graphical User Interface

As shown in Figure 2, the GUI consists of a window with a menu bar at the top, a bar graph of the spectrum in the middle, and a status bar to the bottom. The height of each vertical bar in the spectrum represents the number of pulses that have been detected at a particular energy level (referred to as a *channel*). So the x-axis represents deposited energy, each bar width typically spanning one kiloelectron-volt (keV) of energy, and the y-axis represents the pulse count. The longer the data acquisition continues, the larger the count range represented by the y-axis, because the spectrum is rescaled to fit in the window with every update.

If there is too much noise in the signal, the counts in the lowest energy channels will washout the energy peaks at higher channels due to automatic rescaling of the y-axis. To recover, exclude the noisy channels from the region of interest (ROI).

During live updates, text overlaid at the top of the bar graph area reports the pulses detected over the prior interval, along with the current temperature of the SiPM array in degrees Celsius (C). When a previously saved spectrum is reloaded into the GUI, the text may display 0 CPI and 0.0 C temperature, because this information was not stored in the spectrum file. When the detector module is damaged or disconnected, the temperature will be replaced with dashes. If a negative temperature is displayed at room temperature, an internal reset has occurred in the temperature sensor inside the detector module and the MCA needs to be unplugged from USB power in order to reinitialize the sensor.

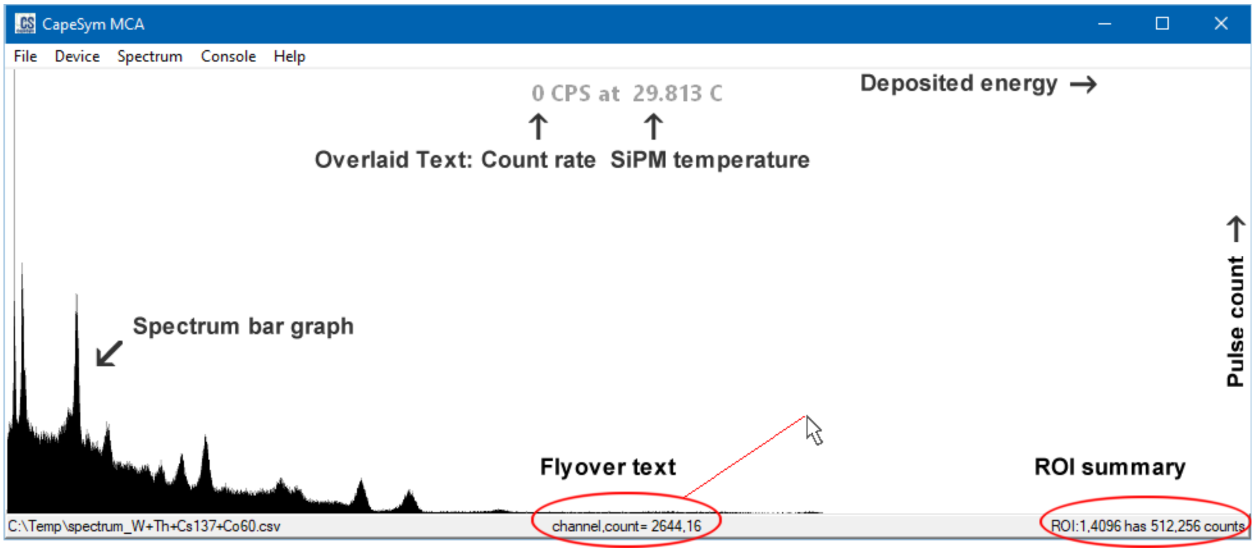


Figure 2: Key features of the graphical user interface are labeled. The horizontal axis represents deposited energy and the vertical axis represents the number of pulses in each energy channel.

The status bar at the bottom of the main window displays three text fields. On the right side is the name of the loaded file or the most recently saved file. The middle text field displays the channel number and count in the bar under the mouse pointer. This field is continuously updated as the pointer moves in the window. The left side of the status bar displays a summary of counts in the current region of interest.

Menus

A conventional menu interface is provided at the top of the Window, with file-oriented operations under the File menu on the left side and helpful information under the Help menu on the right side. The Device menu controls the MCA hardware, while the Spectrum and Console menus control the host software. An important point like this can be easily missed, so such points are repeated in bold text for emphasis.

The *Device* menu is used to make changes inside the MCA,
the *Spectrum* menu is used to change what is done by the host computer.

Region of Interest

The region of interest (ROI) is the range of channels currently displayed in the main window. By default, the entire spectrum is displayed from channel 1 to channel 4095. The total count within the ROI is displayed on the status bar. The ROI may be constrained to a smaller number of channels to focus in on a particular part of the spectrum. The ROI range may be set from the *SpectrumData* menu through the *X-axis range* submenu. When the ROI is modified, the y-axis is scaled automatically to make the largest count in the visible channels fill the height of the graphing area.

The fastest way to change the ROI is to move the scroll wheel on the mouse. Rotating the wheel forward zooms the ROI by narrowing the range. Pulling the mouse wheel back zooms out by expanding the range. When zooming in with the mouse wheel, the channel under the mouse pointer is moved towards the center of the ROI. The ROI can be reset to full range by pulling back on the wheel until the scale stops changing. The left and right arrow keys will shift the ROI to the left or right, respectively.

By dragging the mouse with the left mouse button pressed, a smaller ROI can be selected. The ROI will be set to the channel span of the drag rectangle when the left mouse button is released. The height of the drag rectangle is irrelevant since the y-axis is automatically scaled to the highest spectral component in the ROI. To reset the ROI to the full range use Reset ROI from the *SpectrumData > X-axis range* menu.

Grid lines indicating the y-axis range will be drawn in the main window when the *Draw lines* menu item is checked in the *Y-axis scale* menu. Normally, the y-axis is displayed as a linear scale, but a square root or log scale may be chosen instead from the *Y-axis scale* menu. The y-axis options may be accessed more quickly using the up and down arrow keys.

Spectrum Peak Locations

Local peaks in the spectrum of pulse counts may indicate the presence of characteristic photon energies due to photoelectric absorption or x-ray fluorescence events. Peaks may be selected and tracked in the GUI by clicking on the spectrum with the left mouse button. When the mouse button is released, the software will find the nearest peak and mark it with a vertical line. Multiple peaks may be selected in the GUI by subsequent left mouse button clicks. Unmark peaks by using the right mouse button.

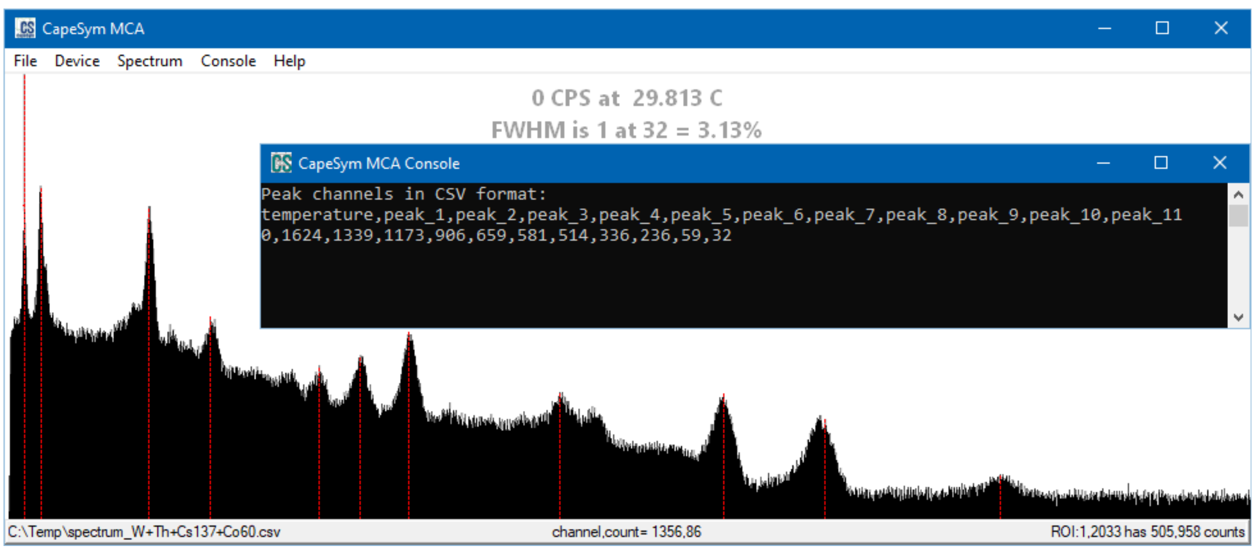


Figure 3: Tracking of energy peaks in the spectrum. Each vertical red line marks the channel location of a local maximum in the spectrum. Channel locations are written to the console.

If the selected peak is tall enough, the full-width at half maximum (FWHM) will also be marked with a horizontal line, and the width (in channels) reported at the top of the graph along with the channel location of the peak. The ratio of FWHM to the peak's channel is also reported as a percentage. When multiple peaks are selected the FWHM computation will only be reported for the last peak selected. FWHM is found by walking down from the peak to find the two channels having less counts than half of the peak count. No curve fitting is done, so it will only work for sufficiently prominent peaks.

A separate console window serves as a blackboard for textual output, including the channel numbers of all of the selected peaks. The console window is hidden by default at program startup but may be revealed by selecting *Show console* from the Console menu. To print the peak locations in the console, select the *Peaks to console* item from the Spectrum menu. As shown in Figure 3, peaks are listed in order of selection. The first entry in the console output is always SiPM temperature, or zero as a placeholder. Any time the displayed spectrum is updated from the MCA or loaded from a file, a new line of peak location data will be written to the console, for as long as the *Peaks to console* menu item is checked.

Peak Tracking

As new spectral data arrive, the channel locations of the identified peaks will be automatically shifted to the new peak locations, so that the selections continue to track growing and shifting peaks. This is particularly important when temperature stabilization is turned off (or when there is no temperature calibration) because channel location will shift dramatically as the temperature of the SiPMs change. Real-time tracking of temperature-dependent peaks is a very useful feature of the host software, especially during the calibration process, as described later in the manual.

Peaks can be tracked in two ways (Figure 4). The peak tracking method is selected by *Peak type* in the Spectrum menu. The default operation is to the track the peak maximum, referred to as the *Mode* of the peak. This maximum can be found easily but it is not likely to be the center of the photoelectric absorption energy distribution (a.k.a. *photopeak*). Switching the Peak type to *Mean* causes the statistical mean to be tracked.

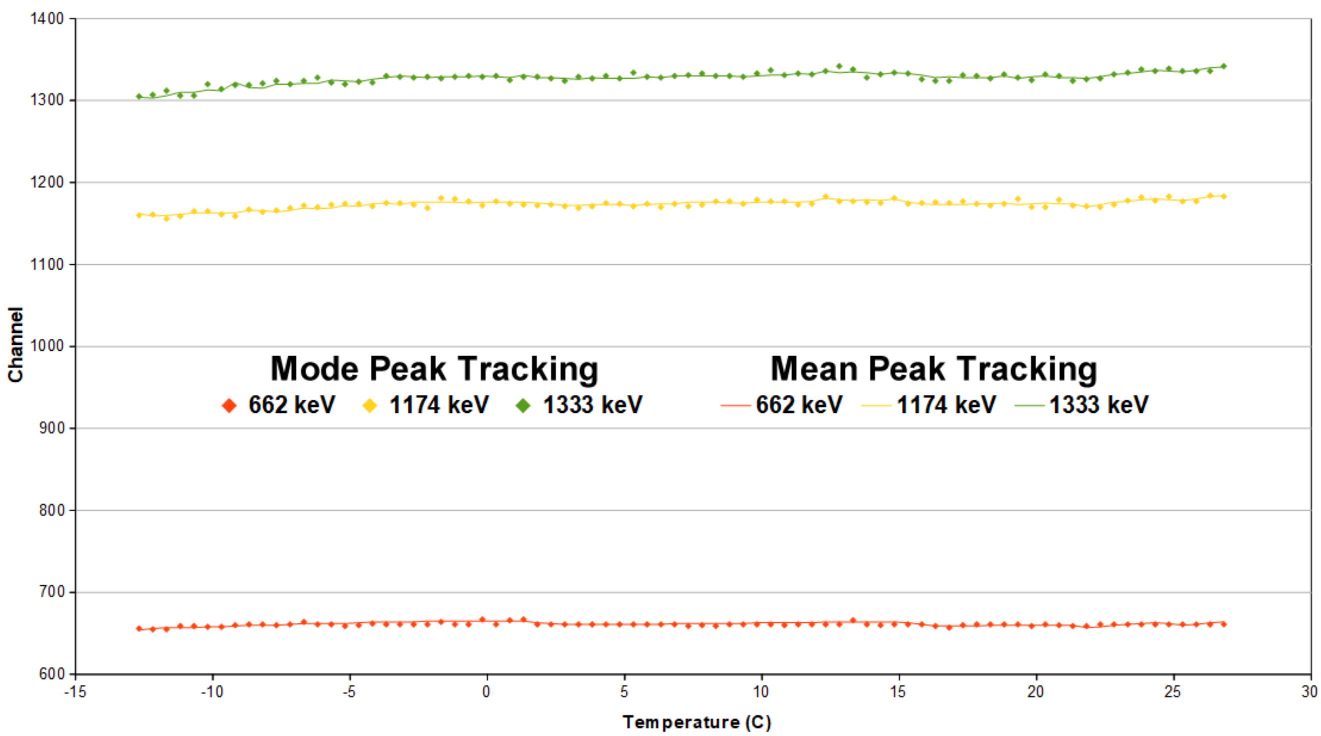


Figure 4: Tracking of Cs-137 and Co-60 photopeaks during a rise in temperature from -13ºC to 27ºC. The diamond symbols denote the channel location of the mode of each peak, while the lines follow the channel location of the mean of each peak.

The statistical mean is computed just for the part of the photopeak above the full-width at half-maximum height. When the underlying probability distribution is normal, the mean will tend to give a channel location closer to the Gaussian maximum. Note that the half-maximum (of the mode) must be above the background in order to track the mean. When the half-maximum level falls below the background, or when two peaks merge above the half-maximum level, mean tracking may lose the peak.

Peak Labels

Spectrum peaks can be labeled with their characteristic gamma energy, expressed as an integer in keV. These peak labels do not change with live updates, unlike the peak channel locations reported to the console. Peak labeling is enabled by selecting the *Label peak when add* from the Spectrum menu. When peak labeling is enabled, each left mouse click will be followed by an input dialog for entering the integer label (Figure 5). The label is then displayed in red text just above the peak indicator line. Peak labels will also appear in the header line in the console instead of the generic categories (peak_1, peak_2, etc.) when the *Peaks to console* mode is enabled.

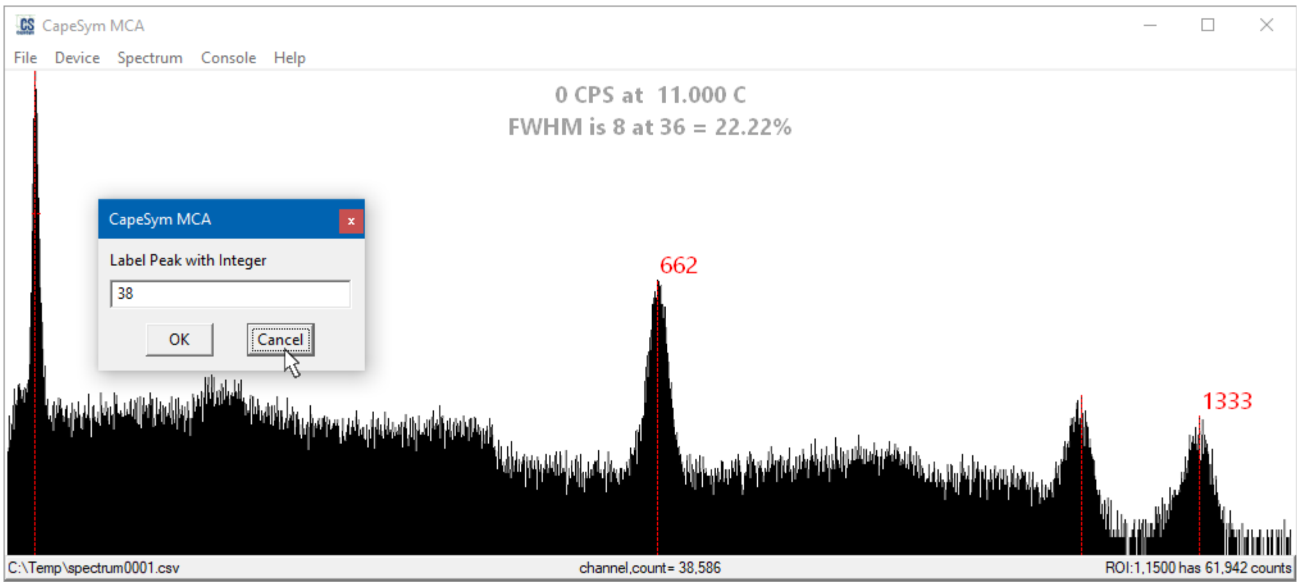


Figure 5: A left mouse button click on the far left peak in the spectrum opens a dialog for adding an integer label. The channel under the mouse pointer is offered as the label, but this can be changed. The Cancel button will skip the label while still marking the peak location for tracking.

Labeling may be applied to some peaks and not others. Just hit the Cancel button when the label dialog appears, as shown above. Peak labels are cleared (along with the peak lines) with the right mouse button. Disable peak labeling by unchecking *Label peak when add* in the menu.

Saving a Spectrum

Any spectrum displayed in the GUI may be saved to a file by using the File menu (Figure 6). It is not necessary to *Disconnect* the MCA to save the current spectrum, however the spectrum will continue to update every second even while the save dialog is open. Disconnecting the MCA will stop further screen updates and allow a particular observation to be saved, while the MCA continues to count pulses.

The format to use for the spectrum file may be changed through the file type selection. The default file format for a spectrum is Comma Separated Values (CSV). For a different file format, use the *Save as type:* list box in the dialog to select from the list of available file formats, such as SPE, CHN, and N42.

The CSV format is written in plain text, each line of text containing the channel number and count separated by a comma. The first channel is 1, so there is no count rate or SiPM temperature information included in the CSV file when using the *Save spectrum...* menu item. This information is encoded in channel zero during live updates. When using Auto Save mode, the zero channel may be optionally added to all CSV saves so that every spectrum will include temperature, which may be important for assessing temperature stabilization after re-calibration.

The N42 file format that is written using *Save spectrum...* contains only channel counts and temperature. For the fuller N42 spectrum format, including acquisition and dead time durations, use the *Record N42 file...* menu item. This menu item is discussed further later on. See Appendix B for complete file format descriptions.

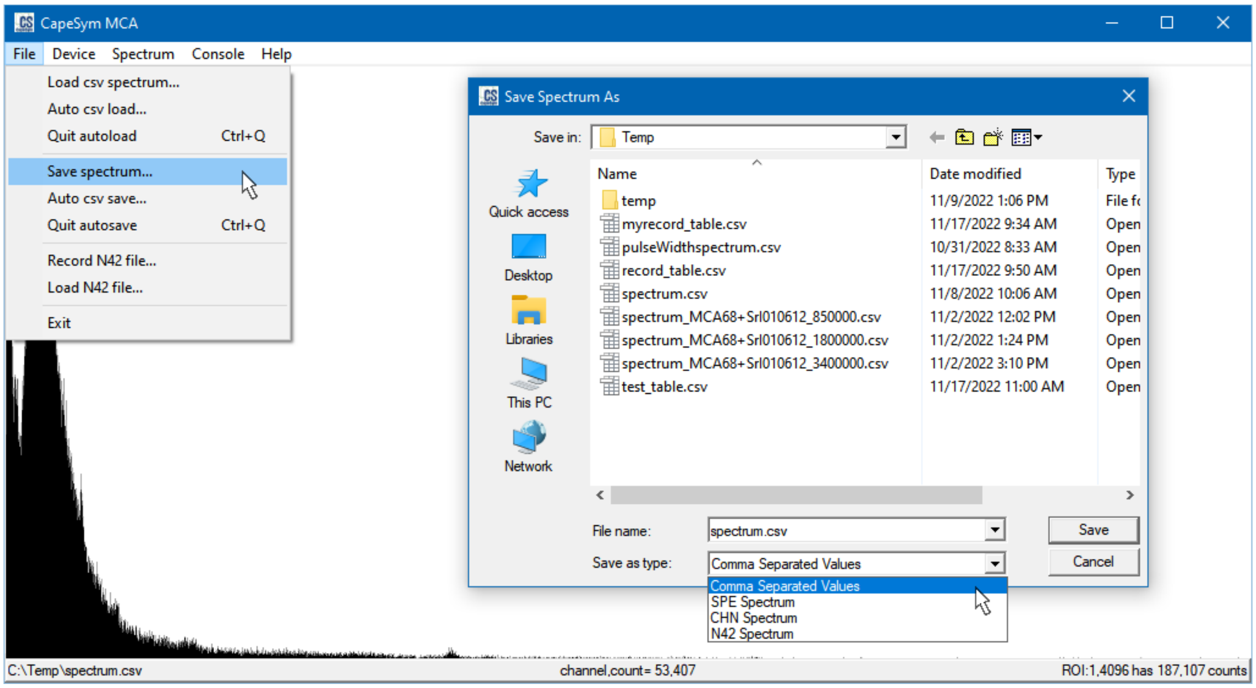


Figure 6: One way to save the spectrum to a file is to use the Save spectrum... *menu item from the File menu. Other ways to save: record spectra to an N42 file or use the Auto Save feature.*

Auto Save

The Auto Save feature is designed to monitor live updates from the MCA and save the spectrum to a file once certain criteria are satisfied. Auto Save will only operate when live updates are coming from the MCA hardware. Therefore the MCA device must be connected (and not stopped) in order for Auto Save to function properly. However, depending on the save criteria, it may be possible to disconnect or stop the MCA briefly during an on-going Auto Save operation, if necessary.

The dialog provides several different options for saving spectrum files, including saving a sequence of spectra acquired at different temperatures as required for evaluating temperature stabilization performance. The Auto Save function will only save files in the CSV format, because the files are intended to be reloaded via the Auto Load function to provide peak location data for the calibration. The option to save the SiPM temperature in channel 0 is also needed for the performance evaluation.

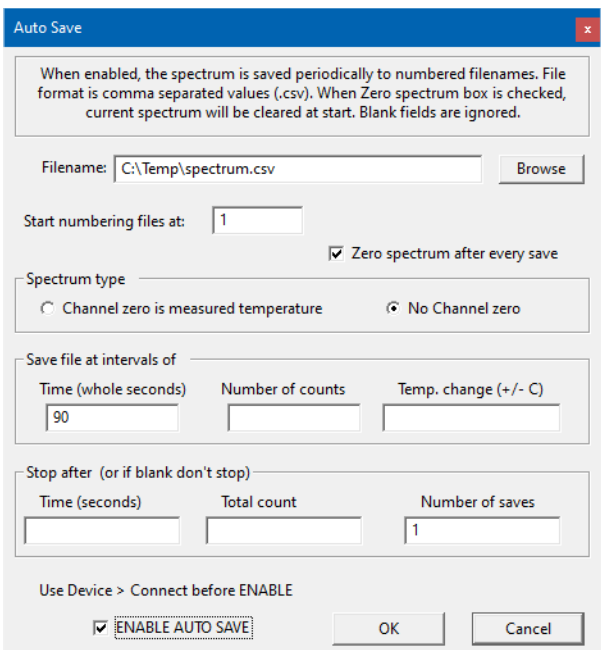
When Auto Save saves a file it appends a number to the filename, so that the sequence of files can be easily reloaded. If the filename already ends in a number, that number is removed and the next number in the sequence is appended. The very first number to use for the sequence is specified in the Auto Save dialog.

The Auto Save dialog entries may be saved with the OK button, without starting the actual Auto Save operation. The Auto Save operation is only started when the ENABLE AUTOSAVE box is checked. Hitting the Cancel button allows the dialog to be exited with keeping any changes. As long as the Cancel button is used, the Auto Save dialog may be opened during an on-going Auto Save operation. Hitting the OK button while an operation is on-going will cause the operation to restart at the beginning of the sequence, or to stop if the ENABLE AUTOSAVE box is unchecked.

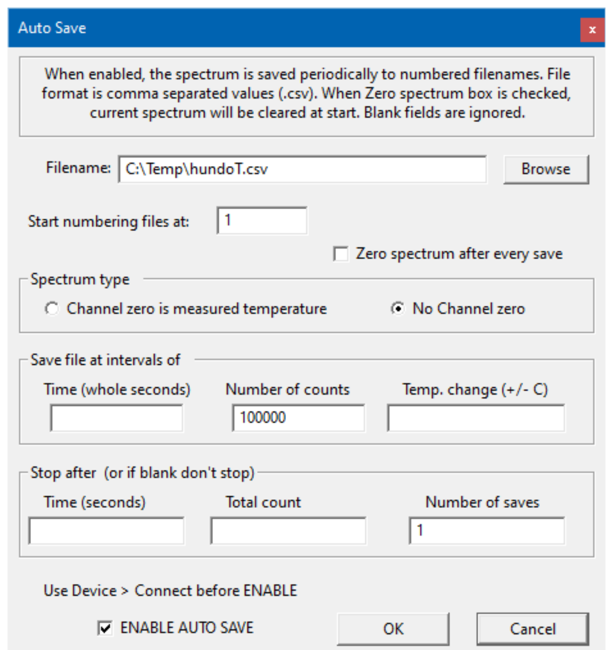
The progress of the Auto Save operation is reported to the console, so it may be helpful to have the console open while auto saving. To stop an on-going Auto Save operation the ENABLE AUTOSAVE box may be unchecked in the dialog (followed by OK), or the *Quit autosave* menu item may be selected.

In addition to saving a sequence of spectra for temperature calibration, the Auto Save operation may be used to perform single or multiple timed acquisitions, or to perform single or multiple acquisitions of fixed numbers of pulse counts. These options are explained with a few concrete examples of dialog settings.

To accumulate and save 90-seconds of data acquisition, use the Auto Save dialog settings shown in Example 1. The current spectrum will be zeroed out and a new spectrum accumulated for 90 seconds before saving it to a file called spectrum0001.csv.



Example 1: 90-Second Spectrum Acquisition

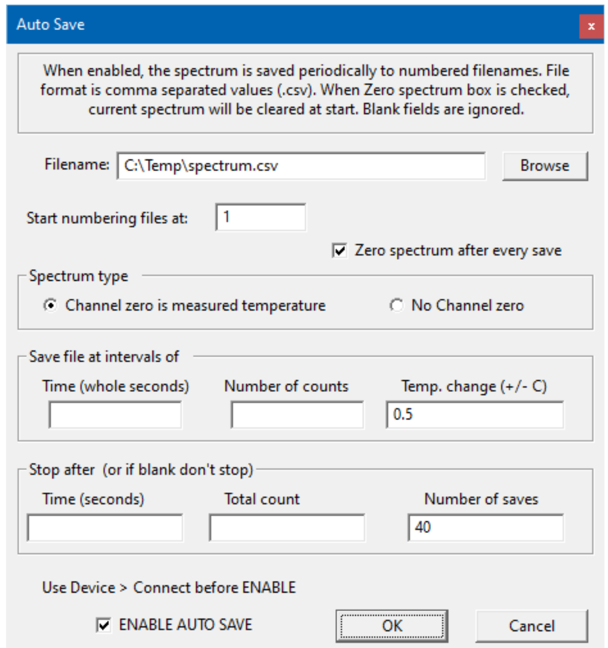


Example 2: Save Spectrum at 100,000 Counts

Example 2 cause the current spectrum to be saved to a file once the total count reaches 100,000. The Auto Save operation is then terminated because the *Number of saves* is set to 1. If the *Number of saves* was set to a higher number, another file would be saved every time 100,000 counts were added to the spectrum. If the *Number of saves* was left blank, files would continue to be added until the user disabled the Auto Save operation. If the desire was to save a new spectrum of 100,000 counts each time 100,000 pulses were detected, then the user should have checked the box next to *Zero spectrum after every save*, so that a fresh spectrum would be started for each 100,000 count accumulation.

The following dialog settings may be used for evaluating the accuracy of temperature stabilization. This Auto Save configuration will save and then zero out the spectrum after every 0.5ºC increase in temperature, until a total change of 20ºC has been recorded. Note that temperature change entered as a positive number causes the save to occur after an increase in temperature. For saves at temperature decreases instead, a negative value -0.5ºC should be entered.

Again, to continue saving indefinitely, the *Number of saves* box could be left blank. In which case the Auto Save feature would be terminated when the user selects the *Quit autosave* item from the File menu. This command is a shortcut for opening the Auto Save dialog, unchecking the ENABLE AUTO SAVE box, and hitting the OK button. The keystroke Ctrl-Q is even quicker.



Example 3: Record Spectra vs. Temperature

Loading a Spectrum

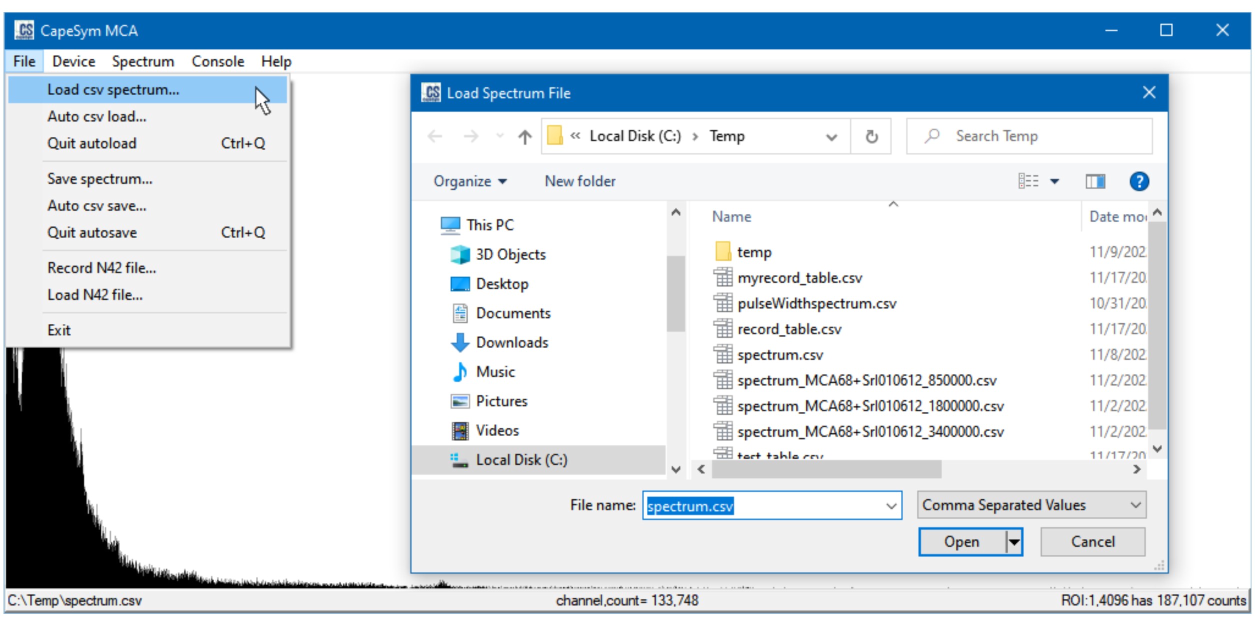


Figure 7: The Load spectrum... *menu item opens a dialog that allows browsing to a .csv file.*

File > *Load csv spectrum...* can be used to load files saved by the application in the CSV format (Figure 7). The MCA device should be disconnected before using the load operation, otherwise the spectrum will be immediately over-written by the next live update. To facilitate disconnection, a prompt is issued before file selection. Responding with "No" to the disconnect prompt will terminate the load operation.

Auto Load

The Auto Load dialog may be used to play back a sequence of spectra recorded using the Auto Save mechanism. Auto Load can be used to create an animated display loop, but its main purpose is to extract peak locations versus temperature for assessing the temperature calibration.

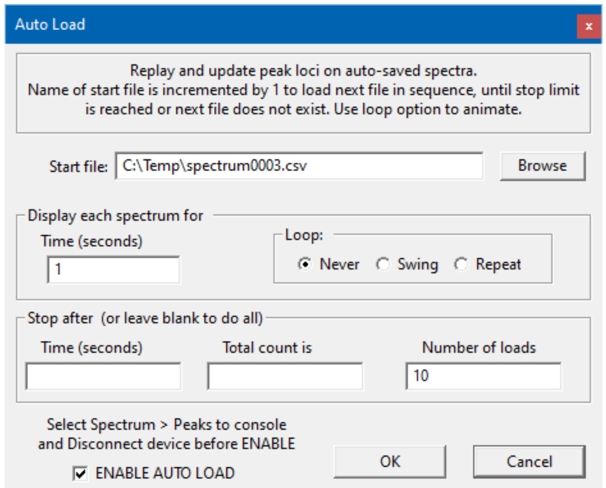


Figure 8: The Auto Load dialog for loading a sequence of spectra saved by Auto Save.

The first file to be loaded is given in the Start file edit box. In Figure 8, the start file is "spectrum0003.csv". That file will loaded and displayed for 1 second, and then the filename will be incremented and the next file "spectrum0004.csv" loaded and displayed for 1 second. After the tenth file has been loaded and displayed, in this case "spectrum0012.csv", the Auto Load sequence will be terminated. The end of the Auto Load operation is reported in a message box.

To repeat the sequence continuously until the *Quit autoload* command is selected, use one of the other *Loop:* options and leave the *Number of loads* box empty. The *Repeat* option will restart the sequence at the start file for each loop. The *Swing* option will reverse the direction of the file loads at the end of the sequence. File number increments will become decrements until end of the sequence and then the direction will again reverse. Note that it is not possible to Swing repeatedly on a sub-sequence of the filenames. With the exception of the starting file, the animation will move from the last file to the first file in the numerical sequence and back again, forever, until manually disabled.

Record N42

The *Record N42 file...* menu item allows multiple radiation measurements to be recorded into a single .n42 file using the ANSI N42.42 (2011) standard with CapeSym-specific extensions. These measurements can then be replayed using the *Load N42 file...* operation. The N42 format is a text-based XML syntax detailed further in Appendix B. The recording filename should have the extension .n42 to signify the N42 XML standard file type.

Use the Record Measurement to N42 File dialog to write the spectrum to an N42 file (Figure 9). First, select a new filepath with the Browse button in the dialog. If an existing file is selected, it will be overwritten without a warning prompt. It is not possible to add measurements to an existing N42 file recorded in a prior session. Specify a duration in whole seconds for the recording. When packet0 is being requested, the software in the host computer can monitor the live time (acquisition time minus the dead time) for the specified duration. Otherwise, recording seconds will specify the acquisition time.

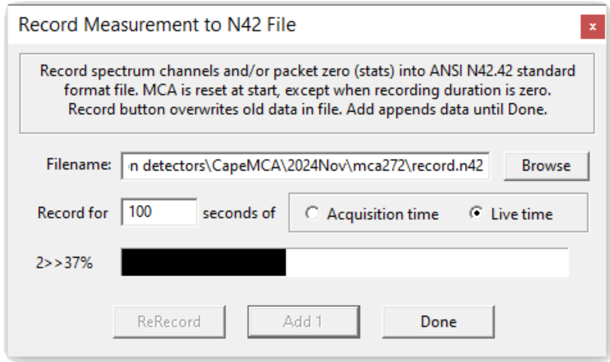


Figure 9: Recording radiation measurements in N42 file format. Start recording with the Record button. After the recording is complete, add another recording to the file using the Add 1 button, or close the N42 file (and complete the N42 syntax) by using the Done button. ReRecord erases the file before recording.

When the Record button is pressed the N42 file will be created and the MCA will be zeroed out. The Record and Add buttons are disabled, and the rest of the menus are inaccessible for the duration. The only allowed action is the Done button, which will be terminate the recording and close the N42 file.

<< The N42 file format is not valid until the Done button is pressed >>

If the duration is set to 0 seconds when the Record button is pressed, the MCA and spectrum are not zeroed. Instead, the current data are immediately written to the file. A spectrum previously saved in CSV format may be loaded and recorded to N42 by using the zero duration option, when the MCA is disconnected. Some information will be inaccurate for zero duration recording, because accurate values are only obtained from packet0 feedback during live recordings. No matter what duration is chosen, the type of data recorded depends on the type of requests currently being made to the MCA. When the software is requesting spectra of 1024 channels, for example, only 1024 channels are recorded.

After the first recording has completed, additional recordings may be added to the N42 file by using the *Add1* button. There is no limit to the number of recordings that may be added to a file, and a different duration can be applied to each added measurement. The N42 recording file will contain the same type of measurements for all recordings, because the type of request can only be changed by exiting the dialog.

Load N42

To examine the contents of any .n42 file recorded by the application, use the Loa*d N42 file...* menu item. This operation does not support all types of N42 formatted files, it only accepts files created with the XML extensions provided by CapeSym. These extensions are defined in an XML schema (Appendix B).

When an N42 file is loaded, the table of measurements is displayed, as shown in Figure 10. Each row corresponds to a measurement contained in the file, as denoted by the identifier (e.g. M1), along with the date, time and duration of the recording. The other fields in the table depend on the request type specified by the Spectrum menu when the recording was done. If the measurement includes a spectrum, then the table will display the number of channels recorded. If no spectrum is present in the measurement, the number of channels will be zero. If the request type included the statistics from packet0 (see below), then columns F through P will contain those numbers. When those columns do not contain data, the packet0 feedback was not being requested when the measurement was recorded.

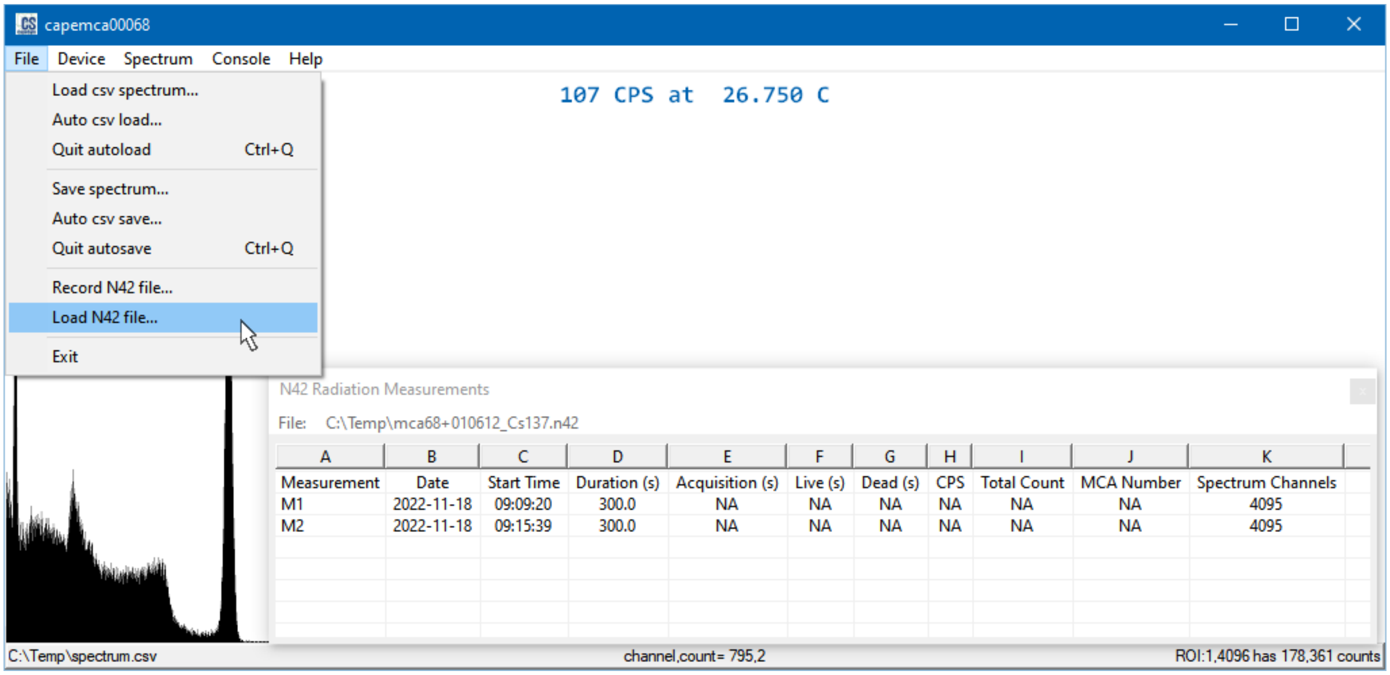


Figure 10: Table of radiation measurements from one N42 file as revealed by Load N42 file...

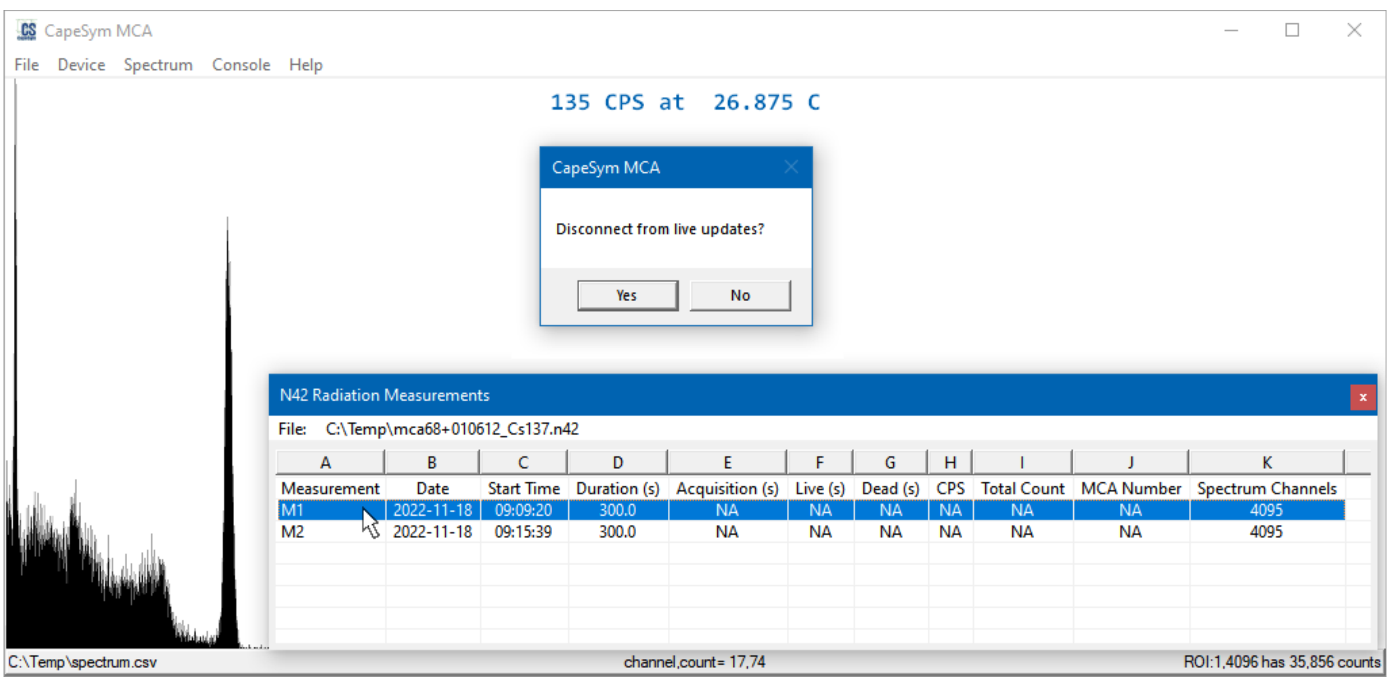


Figure 11: Clicking on one of the rows with the left mouse button will display the spectrum and other measurement information in the main window. If the MCA is connected, then the prompt to disconnect must be answered with the "Yes" button before the measurement data will be displayed.

Measurements in the table can be displayed in the main window with a mouse click, but only when the MCA is disconnected (Figure 11). The display of the measurement depends on the type of request configured in the Spectrum menu, because this determines how the main window is drawn. For example, to see the packet0 statistics, one of the request modes that includes packet0 must be selected in the *Spectrum* menu, otherwise these statistics will not be drawn in the window.

The File menu at the top of the N42 Radiation Measurements table may be used to open another N42 file. This is the same operation as accessing the *Load N42 file...* menu item in the main file menu. The table's File menu also allows the table itself to be saved in CSV format. This is the only way to export the table. The table cannot be copied to the clipboard or otherwise edited. Using Ctrl-C on the table may cause the Connect operation to be executed in the Device menu.

Stream Pulses to File

Another way to save data is to use the streaming dialog to append successive readings into a single file. But this is only appropriate when the data is not accumulative. Streaming is designed to work with pulse lists which only report the events that happened since the previous communication interval. If no events happen in a particular interval, then no data is appended to the file. Figure 12 shows the streaming dialog being used to accumulate 25 pulse lists.

In contrast, the MCA is already accumulating events over time when the spectrum data type is *Pulse counts*, and this accumulated total is returned each communication interval. So streaming these spectra to a file would mostly collect the same data over and over again. It possible prevent this data overlap, by enabling moving spectra (see below) and setting the depth of moving spectra to zero. With these settings, all the spectrum data types of *Pulse counts*, *Pulse widths* and *Pulse sample* are zeroed after each communication interval, such that only events occurring since the prior interval are included. For example, setting the spectrum data type to *Pulse sample* and enabling moving spectra (=1) with depth=0 allows a specified number of pulses to be recorded to a single CSV file.

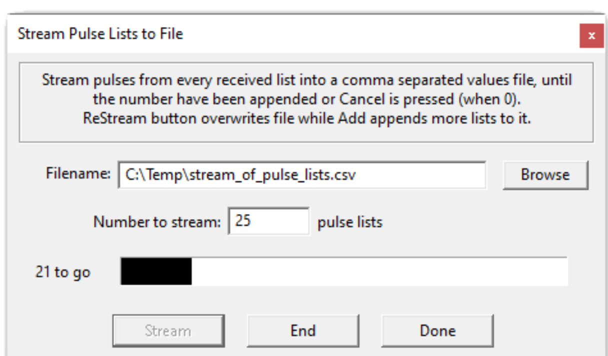


Figure 12: Streaming a sequence of pulse lists to a single file.

MCA Firmware

The MCA firmware contains many parameters that can be accessed and changed through the Windows application. These operating parameters are retained in non-volatile memory while the MCA is powered off. When power is applied, the MCA parameters are loaded into random-access memory (RAM) to facilitate frequent access while the device is powered on. Connecting to the MCA from the host software causes the RAM copy of the parameters to be transferred from the MCA to the host (Figure 13). The parameters may then be viewed and modified in the host software, then sent back to the MCA from the *Update MCA parameters* dialog. The new parameters must be explicitly memorized within the MCA to survive the next reset or power off/on cycle.

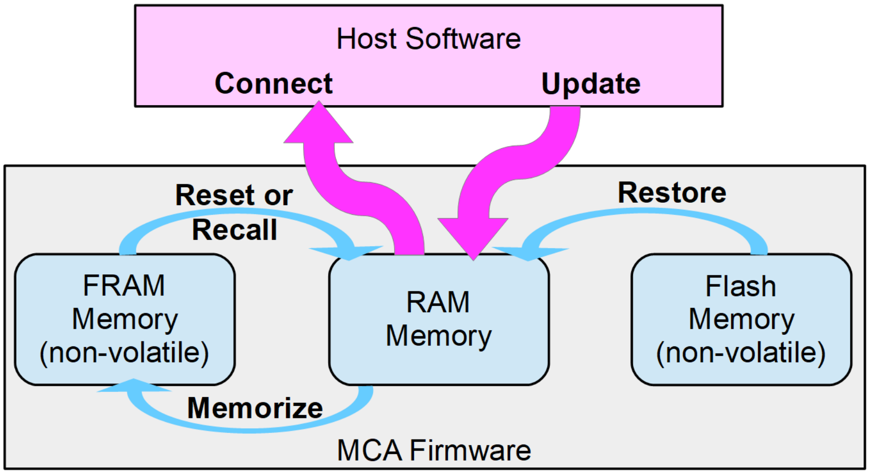


Figure 13: Operations for transferring the MCA parameters.

The user can modify some of the parameters from the *Run mode configuration* submenu of the Device menu (Figure 14), such as turning on and off the temperature stabilization, energy correction, and pulse pileup rejection. These changes are written to the MCA RAM memory at the next communication interval. ***Changes are not retained when the MCA is powered off unless they have been memorized.***

Many of the parameters are modifiable only through the *Stop mode commands* and *Calibrations* menus. The *Calibrations* menu facilitates modification of parameters that provide the MCA with accurate behavior, including those that control pulse pileup rejection, energy correction, and temperature stabilization. When these parameters are modified in the host software, they must be explicitly sent to the MCA in order to take effect, because all pulse processing is done in the MCA firmware.

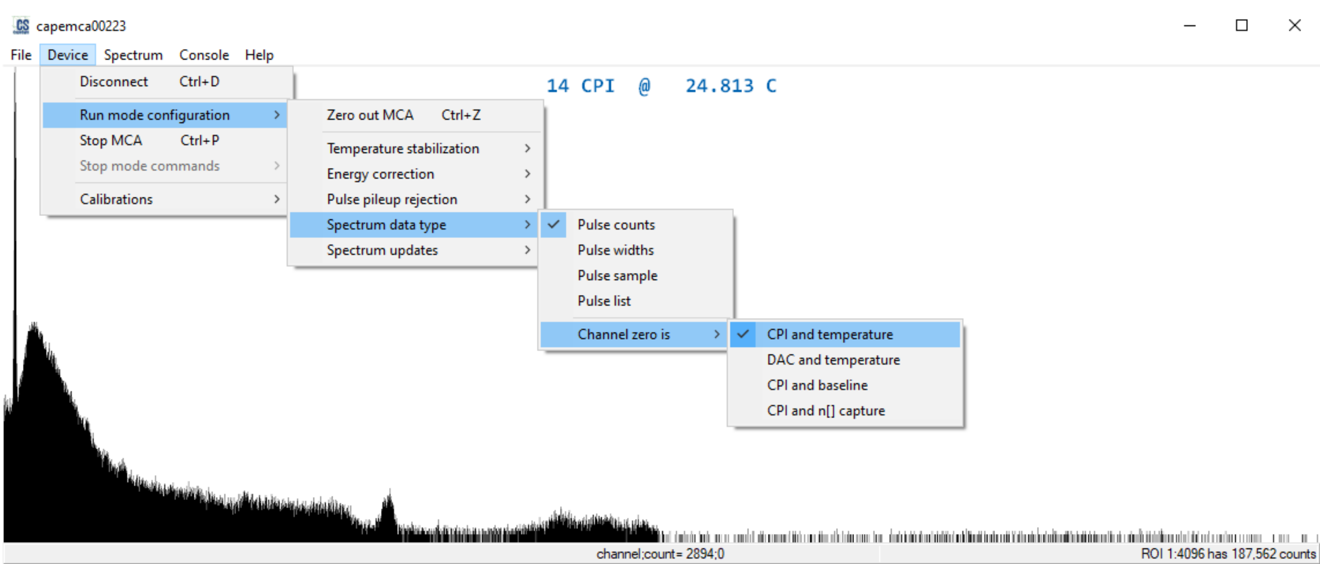


Figure 14: Run mode configuration menu allows some MCA operating parameters to be changed on the fly, including turning on and off the temperature stabilization, energy correction, and pulse pileup rejection, and changing the type of data to be returned as a spectrum and displayed in the window.

Some parameter settings, such as the non-stabilized DAC value, are only applied at startup. Even after they are sent to the MCA and memorized, they do not go into effect until the MCA is reset.

When the USB communications are disconnected, by the *Disconnect* menu item, the host software can no longer adjust the parameters inside the MCA. When the MCA is reconnected the active RAM parameters are again transmitted to the host software from the MCA. Any settings or calibration changes made in the host software while the MCA was disconnected will be over-written by the *Connect* menu item. To preserve parameter changes, the user must transfer them to the MCA BEFORE disconnecting.

When power is removed, the MCA parameters in RAM are discarded so that the device will return to the default state of operation when powered back on. To retain the MCA settings during power-off, the parameters in RAM must be transferred to the MCA's non-volatile memory before unplugging it. This memorization of the MCA parameters is done from the *Stop mode commands* menu, which is only available when the MCA is taken out of Run mode and put into Stop mode.

Run Mode Configuration

The default mode of operation for the MCA device at power-up is *Run mode*. In Run mode, the data acquisition and pulse processing loop is running almost all the time. There is a short break in pulse processing at regular time intervals to allow the accumulated pulse data to be transferred to the host application via USB. This break in processing lasts for a few milliseconds, depending what other processing is enabled. For example, if a moving sum of spectra is being used, this sum must be updated before the spectrum is transmitted. The sum of spectra can require an additional 8 ms to compute, when a large number of spectra are being added together.

As noted above, the *Run mode configuration* menu allows several MCA operating parameters to be changed while the MCA is in Run mode. Only one parameter change can be made during each break for communications, and only if data has not been already requested. Requesting data prevents any other command from being processed until the next communication interval.

<< Only one command is processed per communication interval >>

Change requests sent from the host software are processed by the MCA firmware at the end of the communication interval. For example, with a communication interval of 1 second, the *Zero out spectrum* command would be processed within about a second, and then another second would be required to get the first spectrum of new data. Attempting to make several requests within a single communication interval will result in all but one of the requests being ignored by the MCA.

Changing the communication frequency to 10 Hz would allow 10 commands to be processed per second, while changing the communication frequency to 0.1 Hz would allow one command to be processed every 10 seconds. Starting in version 1.3.5 of the host software, the communication interval can be changed while the MCA is in Run mode, through the *Spectrum updates* submenu, as discussed further below.

Zero Out MCA

The MCA continuously accumulates a gamma energy spectrum in its default operating mode. A count is accumulated forever in each of the 4095 energy channels, as well as in the total count of packet0. Each channel counter is a 32-bit unsigned integer that can reach 4,294,967,295 (2^{32}-1) after which the channel rolls over to zero. The packet0 counter uses a 32-bit floating point value that avoids rolling over but sacrifices some accuracy at such large numbers. All of the counters can be zeroed out from the host application by issuing the *Zero out MCA* command. The MCA is automatically zeroed on reset, or whenever the spectrum data type changes. The MCA may also be zeroed periodically by the Auto Save or

N42 recording functions. Neither the spectrum nor packet0 are retained when the MCA is powered off.

Spectrum Data Type

The type of channel data collected by the MCA and transmitted over the host interface is determined by two main parameters: *Spectrum data type* and *Feedback type*. The feedback type parameter determines the contents of channel zero of the spectrum, while the spectrum type parameter determines what information is in the other 4095 channels. An additional information packet that summarizes the MCA activity, but contains no spectral information, may be also be transmitted, depending on the specific request issued by the host computer. Requesting zero channels results in only the summary packet being sent, hence it is referred to as “packet zero” or *packet0* in the user interface.

Table 2: Types of spectral data transmitted by the MCA over the host interface

Spectrum data type	Channel represents	Spectrum value at channel x is
Pulse counts	Deposited energy	Count of all pulses with x energy
Pulse widths	Deposited energy	Width of most recent pulse with x energy
Pulse sample	Sample index	ADC level of signal at sample x
Pulse list	Pulse index (two channels)	(interarrival interval, integral) of pulse x
Interarrival times	Time bin (1μs wide)	Count of events per interarrival time bin x
Test pattern	Artificial energy	Artificial count pattern at x energy
Time series	Comm. interval number	Value of feedback (e.g. CPI) for interval

Pulse Counts vs. Pulse Widths

Two types of energy spectra may be accumulated in the MCA: the spectrum of pulse counts or the spectrum of pulse widths. The x-axis for both types of spectra is related to the total, above-threshold energy in the pulse, as measured by digital processing of the pulse signal. The y-axis is what distinguishes these two spectrum types. In one case the y-axis is the number of pulses, and in the other case the y-axis is the above-threshold width (in number of samples) of a single pulse.

The default MCA setting will accumulate and return pulse counts for each energy channel. The type of returned data may be changed by switching the *Spectrum data type* (see Figure 14). Selecting *Pulse widths* returns the width of the mostly recently recorded pulse in each channel. (If no pulse has yet been recorded in a channel, the width for that channel will be zero. An actual width of zero is impossible.) The width is expressed as the number of sampling intervals for which the pulse stayed above threshold. The pulse width spectrum is used for adjusting the decay rate parameter, and for pulse pileup rejection (see below).

Pulse Sample

The *Pulse sample* spectrum type allows the user to observe one instance of the sample buffer. The x-axis in this case represents the sample number and the y-axis is the signal level acquired by the analog-to-digital converter (ADC). This MCA output is primarily for debugging the raw pulse signal by directly reading out the sample buffer. For example, it is possible to judge the magnitude of dark current and noise by observing the baseline signal level when no pulse is present (Figure 15).

The *Pulse sample* spectrum data type does NOT provide continuous readout of all pulses, because the sample buffer contains way too much data to transfer to the host software in real-time. With this output, the

MCA digitizes the signal, and detects and processes pulses as it normally would, but when a pulse is detected within the minimum and maximum channel range parameters, the buffer of 4095 samples containing the pulse is copied to the spectrum array.

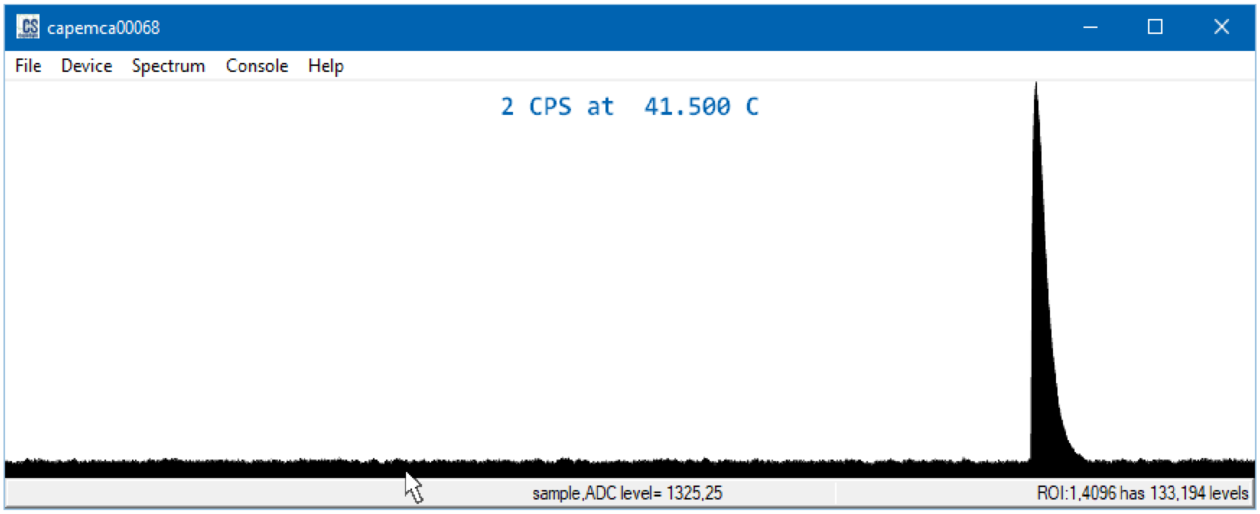


Figure 15: The baseline is the average value of the SiPM signal where no pulse is present, as shown here in Pulse sample mode. ADC level at the pointer is 25, which is a relatively high baseline of 3.3V(25/4095) or about 20 mV, assuming 12-bit ADC resolution.*

There is no accumulation of spectral data in *Pulse sample* mode. At the end of the communication interval, pulse processing is stopped and the data returned in the spectrum is the captured sample buffer. However, the CPI and packet0 still accurately reflect the number of pulses detected during the whole interval. Every interval is of normal duration, whether or not a sample buffer is returned.

The minimum and maximum channel range values can be changed by *Update MCA parameters...* in Stop mode. While the spectrum is limited to 4095 energy channels, much larger pulses are detected and counted by the MCA. These pulses can be observed in Pulse sample mode by setting the minimum and maximum channel range beyond 4095, for example to 5000 and 10000, respectively.

Pulse List

The fourth spectrum data type is for *Pulse list* mode (Figure 16). Instead of the energy spectrum, returned data is the list of pulses detected in the interval. Each pulse is described by its interarrival interval and the integral of the pulse. During detection, the channel of the pulse is estimated in the usual way using the integral divisor and any subsequent energy correction (see below). Only pulses with channel locations that lie within the minimum and maximum channel range parameters are included in the list.

The interarrival interval is the number of samples between the onset of the pulse and the onset of the previously detected pulse in the list. For older firmware versions, the first interarrival interval is the number of samples since the onset of sampling, with a new sampling onset happening after each host communication period. In these older firmware versions, the final pulse in the list gets dropped rather than returned to the host. This bug is fixed in new versions of the firmware issued after Sept. 2024, along with a change to the interarrival interval of the first pulse. In new versions, the first interarrival interval is the elapsed time since the final pulse in the prior (non-empty) pulse list. To be consistent with the other interarrival intervals, this elapsed time is given as the number of samples, up to a maximum elapsed time of ~429 s at 10 Msps. Accuracy of the elapsed time depends on whether the hardware has an external highprecision oscillator. Therefore, the elapsed time might be inaccurate in some versions (see Table 0).

Since each pulse is described by two 32-bit integers, a pulse in the list takes up two channels of the spectrum, with the interarrival interval coming first and the pulse integral second. The first pulse is written to channels 1 and 2, such that interarrival intervals are in odd channels and pulse integrals are in even channels. Figure 16 depicts a pulse list with an arrow pointing to the second interarrival interval in the list.

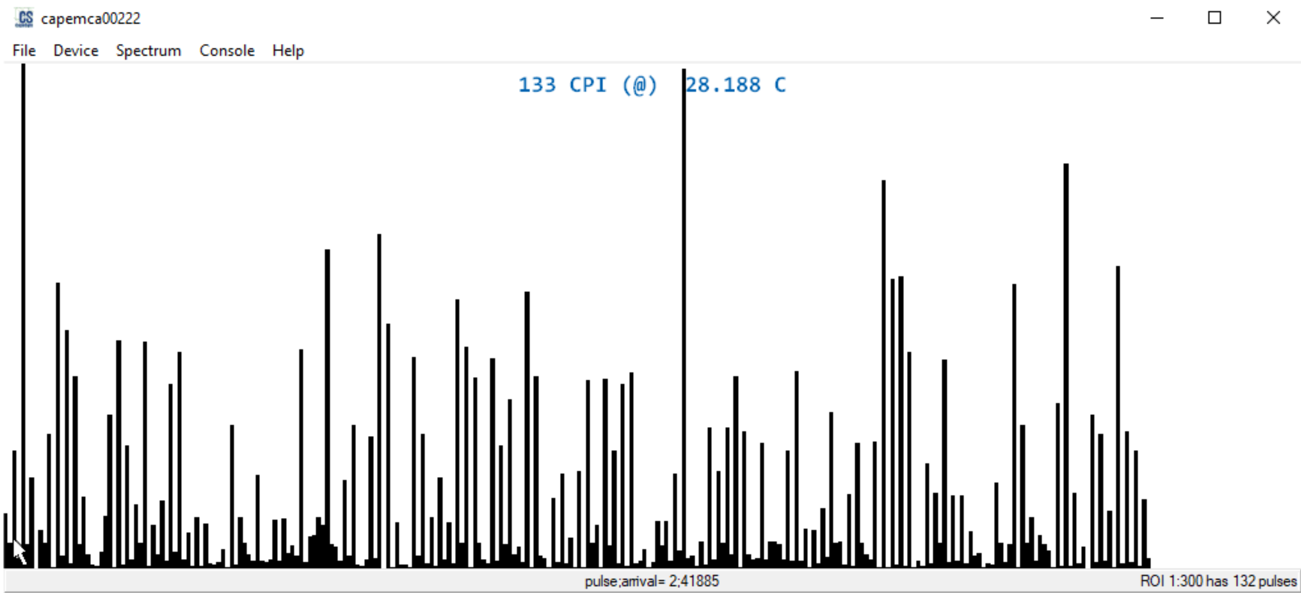


Figure 16: Pulse list showing taller interarrival interval bars followed by smaller pulse integral bars. When the cursor hovers over the interarrival interval of the second pulse, this information is displayed on the statusbar. Note that one pulse detected during the interval was not included in this list of 132 pulses because its channel was not in the specified min/max channel range of [10,4095].

The full pulse list of 4095 channels can contain no more than 2047 pulses. Any pulses which are detected during an interval after the pulse list has been filled will be included in the CPI (channel zero) and CPS (packet0) values, but will NOT be included in the pulse list. Likewise, any pulses that arrive during host communications are NOT included in any pulse list and do not influence the next interarrival time.

Interarrival Times

A histogram of the interarrival intervals between every pair of detected pulses is accumulated and displayed when the spectrum type is *Interarrival times* (Figure 17). Interarrival time is the length of time between the first above-threshold sample in two consecutive pulses. Each bin on the x-axis represents a range of time intervals spanning 1µs. The y-axis value is the number of occurrences of interarrival times that belong in each bin. For example, channel 1 of the spectrum contains the number of interarrival times that were between 0µs and 1µs, while channel 2 contains the interarrivals between 1µs and 2 µs, and so on. The whole spectrum contains counts for interarrival times up to 4095µs. To record longer interarrival intervals, the pulse list output must be used.

The *Interarrival times* spectrum is expected to be an exponential distribution for any radiation source that is stronger than the background. The characteristic shape of the distribution can be used to validate the counting statistics and deadtime correction methods. When displayed in the *Interarrival times* spectrum, the exponential nature of the interarrival intervals can be easily verified by using the *Log base e* scale on the y-axis, which will display the distribution as a straight line. The host software can fit the line and then show an overlay of the slope of the fit in the main window, as detailed in the Counting Statistics section.

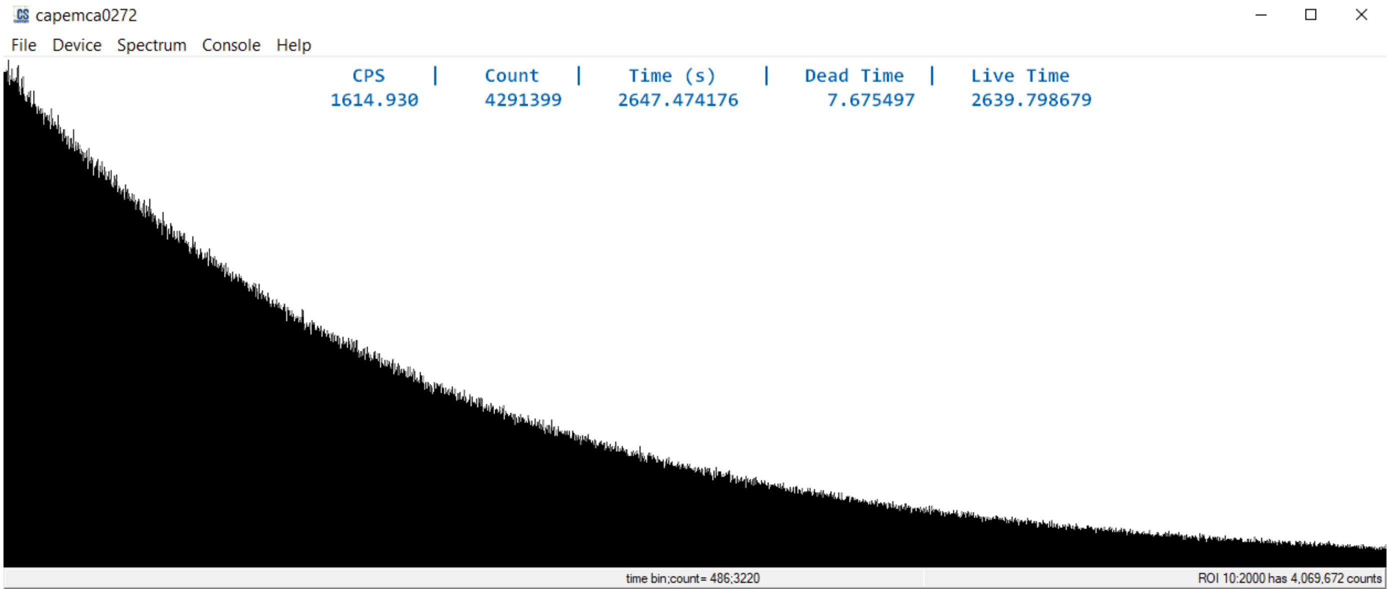


Figure 17: Count of interarrival times in 1us time bins on the horizontal axis. The exponential distribution decays at the mean count rate, consistent with Poisson statistics. See the Calibrations section for details on determining the incoming gamma rate from the curve fit to this distribution.

Test Pattern

Test pattern spectrum provides validation that MCA-to-host communication is functioning properly, even when there is no detector connected to the MCA. The test pattern contains 21 artificial peaks over 4095 channels (Figure 18). The first peak is at channel 99, and peaks occur every 200 channels beyond that.

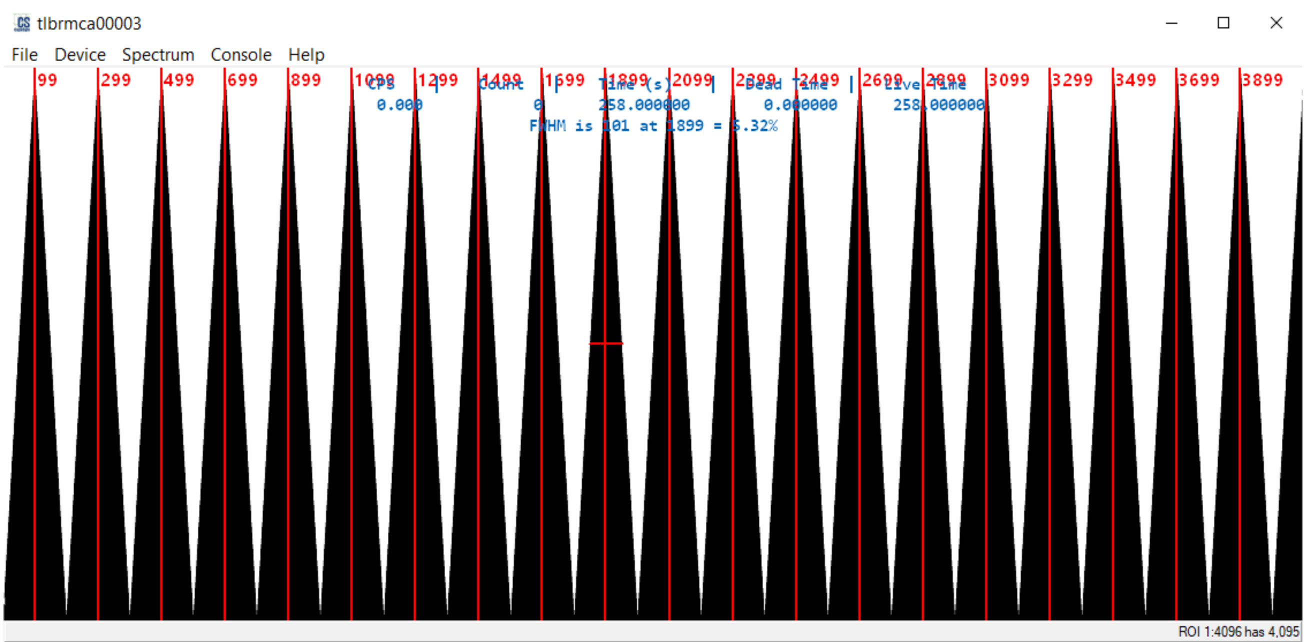


Figure 18: Test pattern spectrum returned by the MCA. The channel location of each synthesized peak is labeled in red. The full width of every peak at half maximum is 101 channels.

When the test pattern is returned no pulse processing is done. The MCA simply waits until the end of the communication interval before returning the precomputed test pattern, so the CPI and other real counts will be zero. Older firmware without the test pattern code may return a pulse list or pulse sample instead of the test pattern when this type of spectrum data is requested.

Time Series

This spectrum data type is a newer firmware feature, available in only a few devices. The spectrum data in this case is a time series of the feeback variable. For instance, if the channel zero feedback is configured to *CPI and temperature*, then the spectrum value at the ith channel is the value of CPI that was returned at the ith communication interval.

When a time series spectrum is first enabled, the spectrum is initialized to all zeros. After the first acquisiton interval, channel 1 would contain the CPI also reported as feedback in channel zero. The next CPI feedback, after the second acquisition interval, would appear in channel 2, and so on. If the acquisition/communication interval is 1 second, then after 68 minutes the spectrum would contain a time series of 4095 sequential feedback values. When the time series exceeds channel 4095, recording begins overwriting data at channel 1, without erasing any of the other channels.

Temperature Stabilization (TS)

Temperature stabilization automatically adjusts the high voltage bias on the SiPM array to maintain a consistent relationship between the energy deposited in the detector and the size of the pulse integral, over a wide range of temperatures. The bias is set by a digital-to-analog (DAC) output from the microcontroller to the DC-DC converter. The DAC value is computed from the measured temperature of the SiPM array, using a set of up to six line segments. Each line segment is defined by three parameters: the starting temperature (t_i), the slope (m), and the y-intercept (b), as follows.

$$\mathrm{DAC} = m\,t + b \quad \text{for}\; t_i \le t < t_{i+1}$$

All parameters are 32-bit integers, so the real values are translated to integers.

$$p_1 = \mathit{floor}(16\,t_i)$$

$$p_2 = \mathit{floor}(100\,m + 0.5)$$

$$p_3 = \mathit{floor}(1600\,b + 0.5)$$

Several methods for determining these parameters are described in the Calibrations section. Parameters must be tuned to the specific MCA and detector for accurate temperature stabilization. Different detectors require different parameters even when the same MCA is used.

The Run mode configuration menu allows temperature stabilization to be turned on and off while a spectrum is being accumulated. Turning off temperature stabilization causes the high voltage to remain constant at its current setting, but it can be adjusted manually using the Calibrations menu. Turning on temperature stabilization will transfer control of the high voltage back to the MCA firmware, which will likely result in a dramatic shift in the channel locations of the peaks of the spectrum as the high voltage is changed. For consistent results, temperature stabilization should remain on after calibration.

Energy Correction (EC)

The energy correction algorithm corrects for the fact that the light emitted from the scintillator is not completely proportional to the energy deposited in the detector. The relationship between deposited energy and light yield is not linear over the entire energy range. The type of radiation can also alter the amount of scintillated light, so energy correction should focus on only gamma radiation photopeaks for consistent results. The calibration table allows up to 32 photoelectric absorption peaks to be associated with known gamma energies. Energy correction also depends on accurate temperature stabilization, so both must be properly calibrated for accurate results.

In the absence of energy correction, the channel in which a pulse will be counted is determined by dividing the integral of the pulse by the divisor parameter *s*.

$$x = \text{channel} = \text{integral} \div s$$

The energy correction is obtained by fitting a quadratic curve to the errors between this channel formula and the known gamma energy in keV (desired channel) for two or more photopeaks. Accuracy of the fit can be improved by including more peaks. Fitted coefficients represent the error in this form:

$$\text{energy - channel} = c_1 + c_2 x + c_3 x^2$$

So energy correction uses the formula

$$\text{energy} = c_1 + (c_2 + 1) x + c_3 x^2$$

The parameters are 32-bit integers so the coefficients are translated into integers as follows.

$$p_1 = floor(10^3 c_1)$$

$$p_2 = floor(10^6 c_2)$$

$$p_3 = floor(10^9 c_3)$$

Note that when energy correction is enabled the parameter p_1 provides the channel offset. By modifying this parameter directly, it is possible to shift the entire energy range represented by the spectrum. For instance, if correction makes channel 1 represent 1 keV, adding 1000 to p_1 would shift the entire energy range for the spectrum such that channel 1 represents 2 keV instead. Adding 4,000,000 to p_1 would shift channel 1 to count pulses that deposit 4001 keV, and channel 4000 would then represent 8000 keV. However, care must be taken to ensure that the quadratic fit is still accurate for these higher energies.

Pulse Pileup Rejection (PPR)

At high count rates, pulses may overlap in time, causing inaccuracies in the mapping of pulse integrals to channel locations. Pulse Pileup Rejection uses the expected width of pulses in each channel to reject overlapping pulses and exclude them from the spectrum. Every pileup is counted as one pulse and included in the CPI information returned with the spectrum. Excluding piled-up pulses from the spectrum helps maintain the energy resolution of peaks during high count rates. The accuracy of PPR depends on many other parameters in the MCA including those of the temperature stabilization and energy correction.

Many types of Macropixel detectors exhibit a characteristic relationship between pulse width and the gamma energy deposited in the detector, as demonstrated by the pulse width spectrum (Figure 19). Pulse width spectra are useful (at low count rates) because they show the expected relationship between pulse width and energy. When count rates get too high, pulses start to overlap making energy measurements of individual pulses uncertain. Most of the piled-up pulses will have pulse widths that are much longer than normal for the measured pulse integral, allowing them to be rejected from inclusion in the spectrum by matching their measured width against the expected width for a normal pulse.

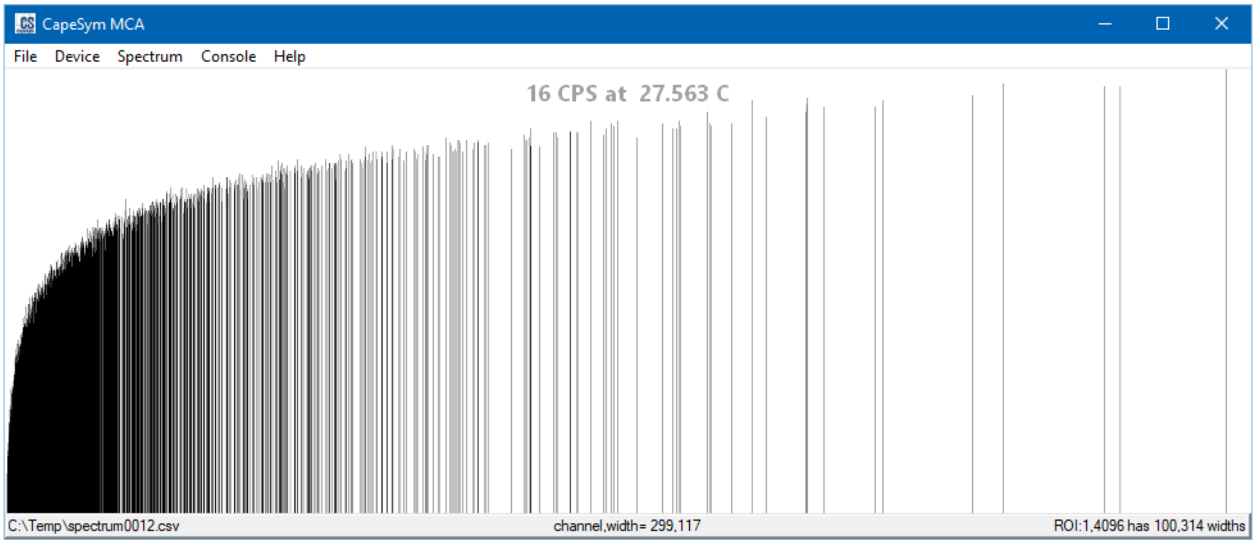


Figure 19: Pulse width spectrum accumulated from dozens of minutes background radiation.

The pulse width, expressed as the number of samples between the first and last threshold crossing, may be reasonably fit by a single curve involving four coefficients.

$$\text{pulse width} = c_1 + c_2 x + c_3 \sqrt{x} + c_4 \ln(x+3)$$

where x is any channel number in the range [1,4095]. The fitting coefficients are calculated by the host software (during PPR calibration) and then stored as signed integers in the MCA's parameters. Each integer parameter is 10,000 times the corresponding real-valued coefficient. The curve is plotted over the pulse width spectrum using *Plot pulse width (PW) limits* from the *Calibrations > Pulse reject/capture* menu, as shown in Figure 20.

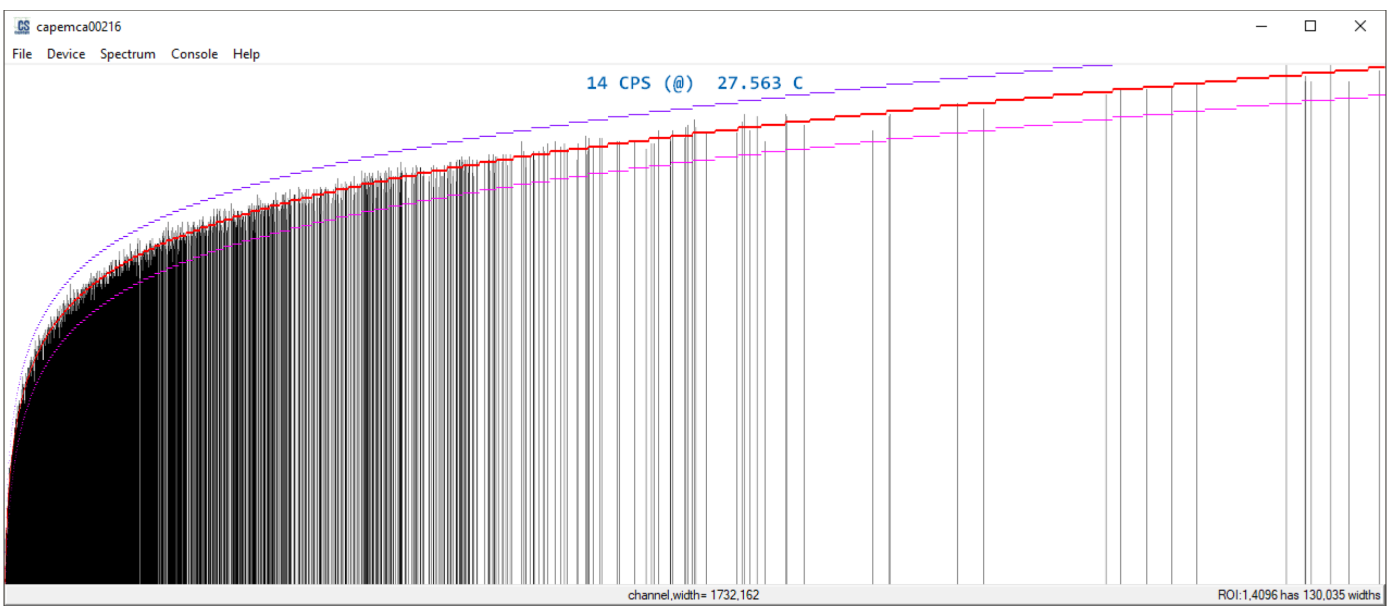


*Figure 20: The fitted curve (*red*) to the pulse width spectrum is plotted along with the upper (*purple*) and lower (*magenta*) pulse width limit curves. Pulses having widths outside the limits are rejected as pile-ups when PPR is enabled.*

The range of accepted (not rejected) pulses is defined by a maximum and a minimum width at each channel, specified by two offset parameters that give the distance above and below the fitted curve. These parameters may be entered by selecting *Enter PW limit offsets...* from the PPR calibrations menu. The default offsets of 10 put the maximum of the accepted width range at 10 samples more than the fitted value, and the minimum at 10 samples less than the fitted value (Figure 21).

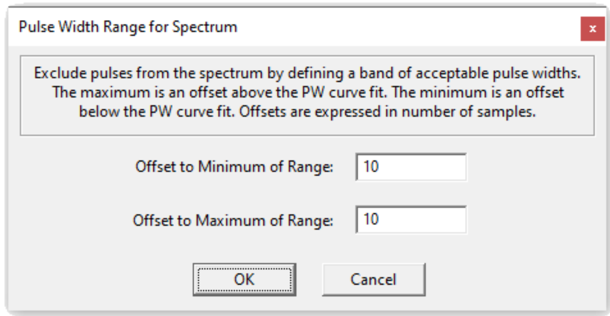


Figure 21: Default offsets for pulse width limits.

Firmware developed recently for faster scintillators operating at high count rates uses a narrow shaping filter with compensation for the slow decay of the pulse. With the proper decay rate parameter, pulse widths will be constant over a wide energy range (Figure Error: Reference source not found). Curve fitting techniques fail in such cases, so a constant pulse width curve should be defined by setting *c1* to 10,000 times the observed pulse width. As shown in the figure, a constant pulse width of 15 means *c1* should be manually set to 150,000.

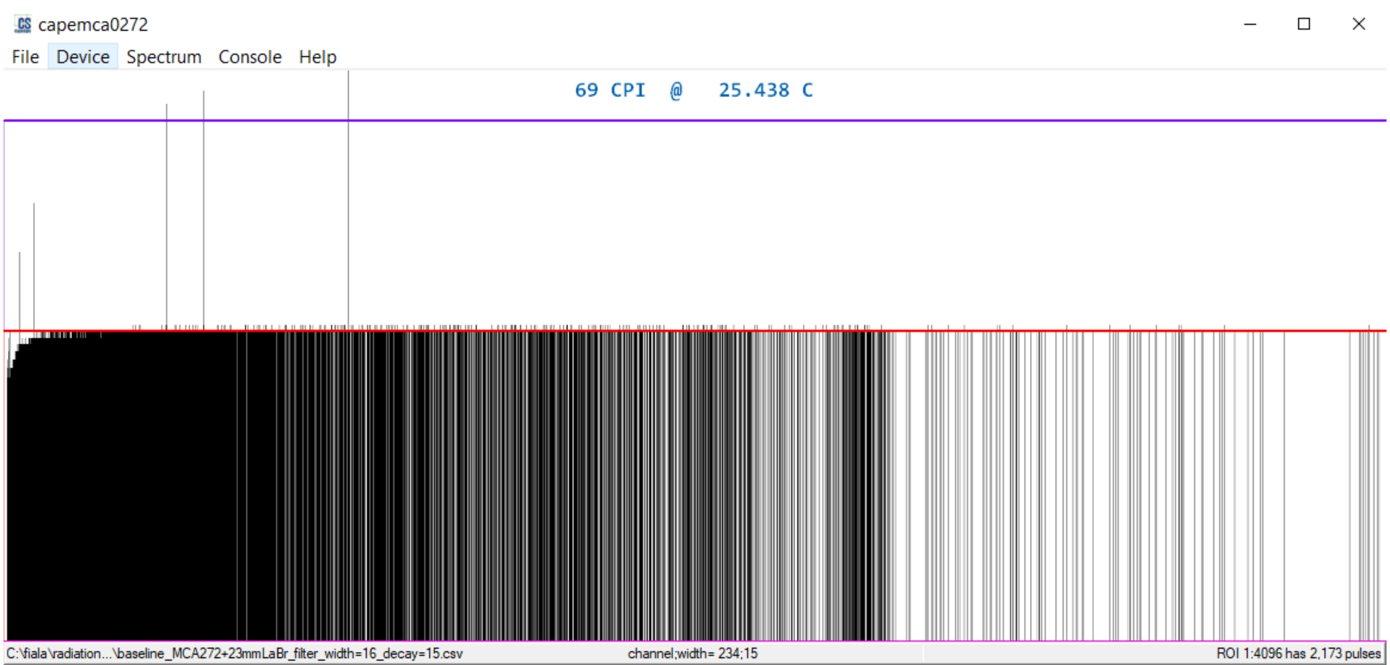


Figure 22: A constant pulse width cannot be fit by the non-linear pulse width curve, so it must be defined by setting the pulse width curve coefficients to {c1=150000, c2=0, c3=0, c4=0} manually in Stop mode. The resulting pulse width limits are displayed in the figure, with the red line representing the pulse width curve with a constant pulse width of 15 samples. The maximum pulse width limit (blue) can then be brought closer to the red line in order to reject all pile ups having much longer widths.

Channel Zero Feedback

When channel zero feedback is set to *CPI and temperature* (see Figure 14), the pulse count is returned in channel zero of the spectrum along with the temperature of the SiPM array. These two values are received in spectrum[0] at every communication interval and displayed at the top of the main window. The pulse count is the number of events that occurred since the last communication interval, so it is displayed as counts per interval (CPI). When the communication interval is 1 second, this number is close to the actual counts per second (CPS). Note that displayed CPI values pertain to only a single MCA, even in situations in which multiple MCAs are connected together in an array.

Table 3. Feedback components available during different types of spectral processing.

Spectrum Type	**Allowed Content in Channel Zero**						**Packet0**
	CPI	**NPI**	**baseline**	**DAC**	**Temp.**	**Current Monitor**	
Pulse counts	●	●	●	●	●	●	●
Pulse widths	●	●	●	●	●	●	●
Pulse sample	●	N/A	●	●	●	●	●
Pulse list	●	N/A	●	●	●	●	●
Interarrival times	●	N/A	●	●	●	●	●
Test pattern	N/A	N/A	●	●	●	●	N/A
Time series	●	●	●	●	N/A	●	N/A

CPI: Counts per interval, NPI: capture box count per interval, DAC: digital-to-analog level for bias voltage

The spectrum[0] format consists of two 16-bit values for all channel zero feedback options, as detailed further in Appendix A. The CPI value is stored as a 16-bit integer in the upper 16 bits of spectrum[0]. The 16-bit width limits this feedback to 65,535 CPI, beyond which the message OVER is displayed in the main window. To see the current count rate in this case, the CPS value in packet0 must be used instead of CPI, by switching the *Request # of channels* in the Spectrum menu.

The SiPM temperature is stored in the lower 16 bits of spectrum[0]. To handle the fractional part of the temperature, the 16-bit integer stored is 16 times the actual temperature reading. For example, 25.25°C would be stored as the integer 404 because 404/16 is 25.25.

DAC and Temperature

During calibration of temperature stabilization it is helpful to get feedback about the digital-to-analog converter (DAC) voltage that controls the high voltage bias on the SiPM array. When *DAC and temperature* is selected, the count rate is replaced with the DAC level (a 12-bit number in the range [0,4095]), and the value is displayed at the top of the window. This DAC value is the commanded value, so when temperature stabilization is turned on it will not be equal to the DAC parameter value reported in the MCA parameters dialog. More about the relationship between DAC level and high voltage bias can be found in the temperature stabilization section.

CPI and Baseline

The third option for channel zero feedback is CPI in the most significant 16 bits and the SiPM signal baseline value in the lower 16 bits. The baseline value is between 0 and 16384, reflecting all possible readings of the analog-to-digital conversion (ADC). The maximum level is 16384 for 14-bit ADC, and 4096 for 12-bit ADC. The ADC values represent voltages from 0 V to 3.3V. At room temperature, the baseline should be no more than a few mV for a small detector module. However, higher baselines values will occur for larger SiPM arrays, or at high radiation levels or high temperatures (see Figure 15). Persistently higher baselines at room temperature may be an indication of degraded SiPMs or detector module damage allowing entry of ambient light.

CPI and n[] Capture

The fourth feedback option is CPI and n[] capture rate, the latter being the number of CPI events that were also within the capture box region. CPI will include every count in the spectrum and capture box, plus any pulses excluded by pulse pileup rejection, if enabled, as well as those pulses too big or too small to lie within the spectrum's channels. The CPI includes all pulses detected during the last interval (between green LED flashes) as determined by the MCA's communication interval parameter.

“Detected” here means the pulse exceeded the threshold for the minimum number of samples, typically 16 samples for the standard 5 to 5.56 Msps sampling rates or 32 samples for the 10 to 11 Msps sampling rates. In firmware that features an adjustable filter width, the minimum number of samples above threshold for detection is usually set to half of the filter width parameter. In other words, a filter width parameter of 16 requires that a pulse be above threshold for at least 8 samples to be detected.

The capture box defines a region of the pulse width versus channel measurement space. The capture box can be used to count the subset of pulses that have unusual pulse widths. For instance, the capture box could be used to count pulses in a certain energy range that exhibit a pulse width deficit (Figure 23). These high-energy, shorter pulses may be typical of neutron capture events in certain types of scintillators containing lithium.

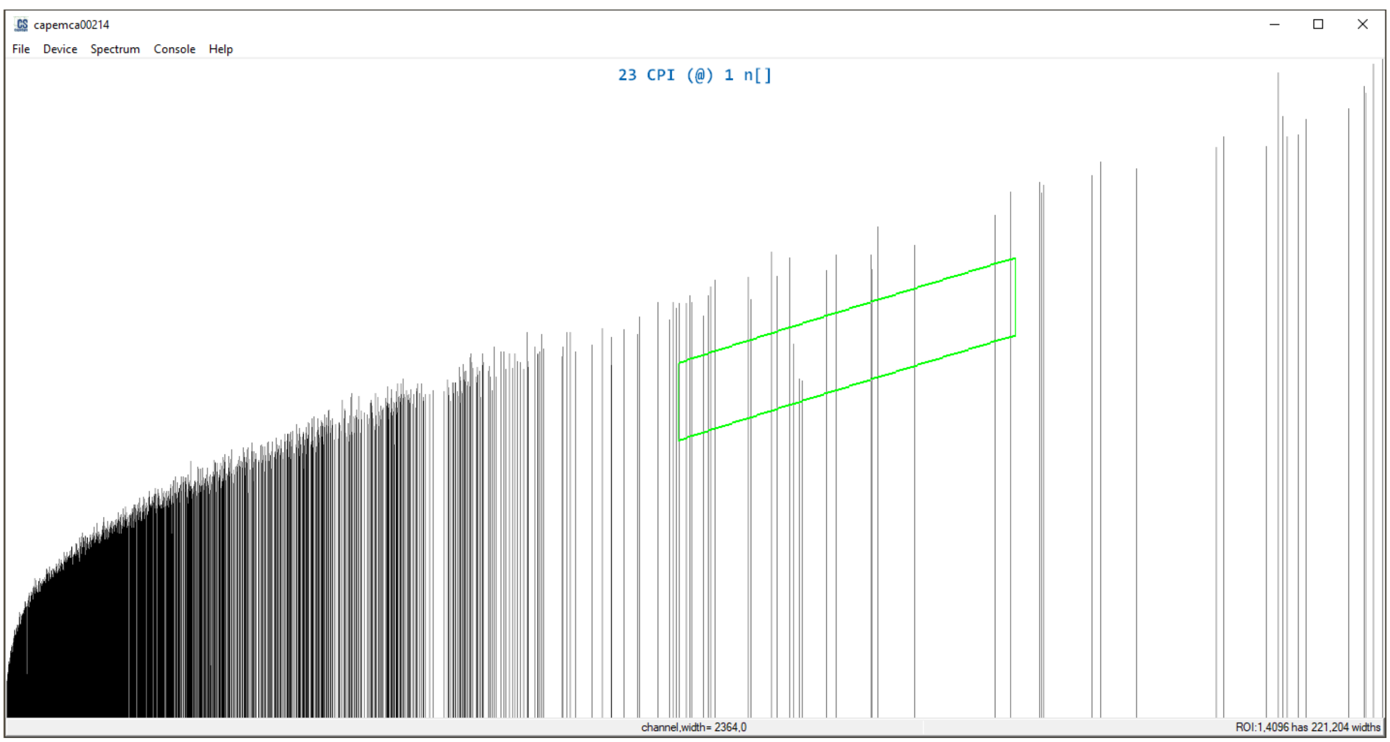


*Figure 23: The capture box region (*green*) plotted on top of the pulse width spectrum. Counts within this region are displayed by selection of* CPI and n[] capture *for the channel zero feedback. The count per interval within the box (*n[]*) is shown along with the total count per interval (*CPI*).*

The *Pulse reject/capture* menu is used to setup and display the capture box region. However, the gamma pulse width spectrum must be fit with a curve via the *Fit curve to PW spectrum* menu item before defining the capture box, because the box is defined using offsets from this pulse width curve. Once the pulse width curve is established, setup the capture box using the *Enter box parameters...* menu item. In this dialog, the offsets define the pulse width region relative to the fitted PW curve. The offset to the maximum PW defines the top of the box, whereas the larger offset to the minimum PW defines the bottom of the box. The channel minimum defines the left side of the box and the channel maximum defines the right side of the box. All pulses that land within the box will be included in the n[] count per interval feedback.

Spectrum Updates

The *Spectrum updates* menu allows the frequency and source of spectral data to be modified while in run mode. These menu items change one of the operating parameters, modifying the parameter in the MCA firmware on the next communication interval. If the MCA is part of an array, the parameter change will be forwarded to the other MCAs as part of the packet0 data sharing that happens at every communication interval. The spectral data returned to the host software may come from just the one MCA connected to the host via USB, or from the whole array, depending on the selection in the *Source memory* submenu.

Update Interval

The *Update interval...* menu item displays the current communication interval parameter and allows the user to change it. The parameter specifies the interval in 100ms increments. A value of 1 is 100ms and a value of 10 is 1000ms, as discussed further below. The frequency of spectrum data requests made by the host software will also adjust to the new frequency. The host software limits the maximum interval value to 20 (2s) but a longer interval can be programmed by modifying the MCA parameter in Stop mode. Caution should be used with longer intervals because the MCA becomes much less responsive to further changes.

Source Memory

Spectral data received by the host usually comes from an array of 4096 memory locations in the MCA. The MCA accumulates pulse counts continuously in this array until the spectrum is zeroed or the device is reset. This default source of spectrum memory will be indicated by a check mark next to the menu item: *1 MCA, since reset*. Instead of accumulating a single spectrum forever, the MCA can be configured to keep only spectral data acquired during the last few intervals, with the channel counts from the most recent interval being shifted into a larger multiple array memory while the counts from the oldest interval are shifted out and forgotten. Hence the term “moving spectrum”, which corresponds setting the *Moving spectrum* parameter to 1.

When there are multiple MCAs configured in an array, with MCA-to-MCA communication links between them, the source spectral data can be *All MCAs in array.* The spectral data from all of the MCAs is passed to the one MCA connected to the host just prior to processing the host request. The data are combined to form a single spectrum that is transmitted to the host. The spectrum source memory in this case is the sum of the single array memory of every MCA in the array. It is not possible to use moving spectra while combining array data in this way, because these spectra are accumulated forever until zero or reset.

For a single MCA configuration, the *1 MCA* items are the only possibilities. Choosing the third option will result in the same result as choosing as the first option. Choosing the moving spectrum option for an array will cause every MCA in the array to also switch to moving spectrum mode such that the packet0 information will track only the most recent data acquisition intervals. When the detector or radiation source is moving, the *Moving spectrum* option may be combined with the source direction feedback to facilitate continuous source tracking. All of the MCAs in the array must be configured the same way, with moving spectrum enabled, and with the same depth and communication interval.

Interval Depth

The depth of moving spectra memory specifies how many intervals will be retained, to be later summed into one spectrum and returned to the host. For example, a value of 8 will retain 8 spectra, each one recorded during a prior interval. When the communication interval is set at 1 second, this would mean that 8 seconds of spectral data is retained in the MCA. The parameter is only relevant when the moving spectrum mode is enabled. Furthermore, the maximum allowable depth depends on the size of the RAM inside the MCA, and so may change with hardware version.

Request # of Channels

Configuration changes discussed so far have involved modifying parameters that are stored inside the MCA. However, the host software can also configure the type of data requests it makes to the MCA, which changes the amount of data that the host will receive in reply. These request types are selected in the *Request # of channels* section of the Spectrum menu (Figure 24). Request types differ in the number of channels of the spectrum returned, chosen from the set of lengths {0,256,512,1024,2048,4096}, as well as in the presence or absence of the additional 64-byte counting statistics data packet (a.k.a *packet0*). Details of the packet0 data structure are presented in Appendix A.

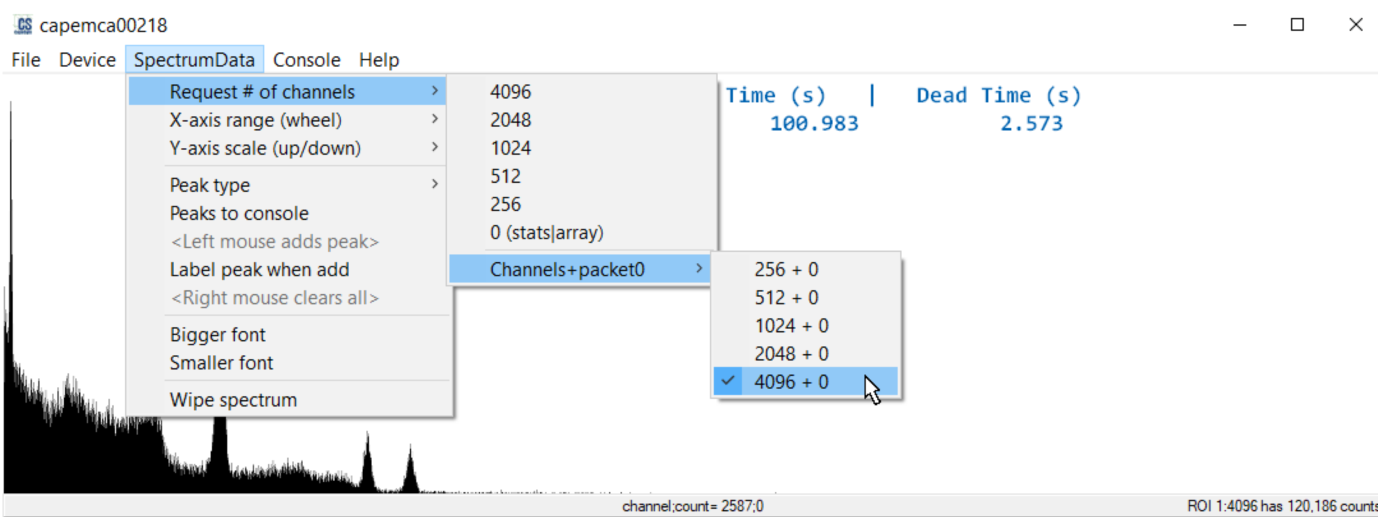


Figure 24: The menu items for configuring the data request during live updates from the MCA. Different numbers of channels in the spectrum may be requested along with the packet0 data. When packet0 is included, the displayed text at the top of the window changes to show some of the returned statistics.

Packet Zero

Packet0 is designed to provide rapid data feedback in autonomous vehicle and other applications which do not require the details of the gamma energy distribution. In addition, packet0 provides information on the total acquisition time (since zero or reset) as well as the dead portion of acquisition time. Some of the packet0 information is displayed in the main window when *Request # of channels* is set to 0, but all of the packet0 fields are stored when N42 file recording is used.

Some packet0 fields have been added to support multiple detector modules interconnected by cables or a *backplane*. When the host software receives a packet0 which reports that more than one detector is present, the additional array information from packet0 is automatically displayed in the main window. This information includes the sum of count rates from all detectors, the total count rate in a specified channel range, and the direction of the source of radiation in the specified channel range. The channel range used for calculating these fields is delimited by the minimum and maximum channel parameters. These channel range parameters may be updated in Stop mode.

Stop Mode Commands

The *Stop MCA* menu item causes the MCA hardware to stop processing pulses from the detector module and to stop accumulating a spectrum. Entering Stop mode allows the MCA firmware to be updated beyond the on/off adjustments available in the *Run mode configuration* menu, through the S*top mode commands* menu (Figure 25). To exit Stop mode, use the *Start up* command on the Device menu, or generate a *Soft reset* from the Stop mode commands menu. When a reset is generated the MCA parameters will be reinitialized from non-volatile memory (see Figure 13), while the Start up command allows Run mode to resume using the MCA parameters that are currently in RAM.

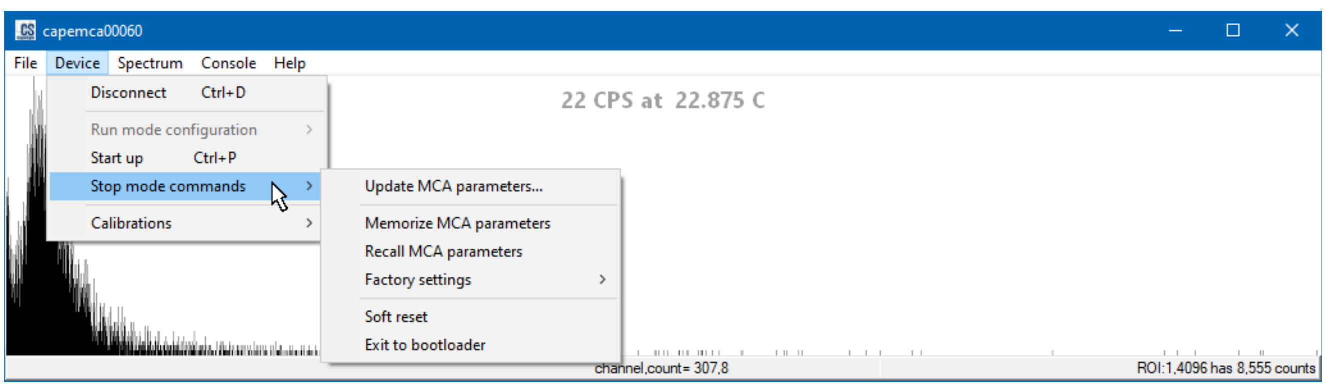


Figure 25: All of the modifiable MCA parameters can be viewed and edited using the Update MCA parameters... *menu item, but many parameters are easier to update from the Calibrations menu.*

Update MCA Parameters

The *Update MCA parameters...* menu item opens the MCA Parameters dialog (Figure 26). The spreadsheet-like interface allows the values in the first column to be edited, while the second column provides a description of the parameter. The purpose and modification of many of these parameters are described in Calibrations section. Most parameters are easier to modify using the Calibrations menu rather than by entering them directly in the MCA Parameters dialog.

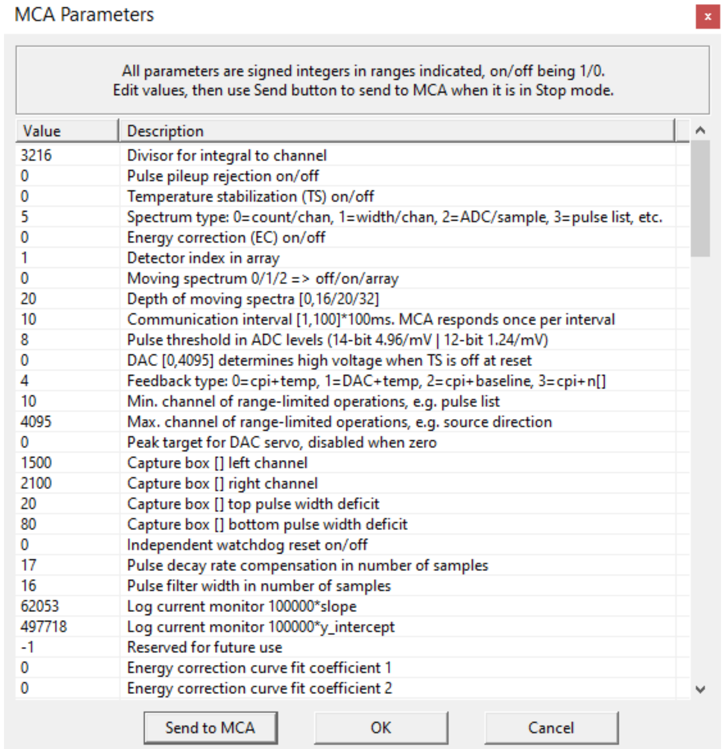


Figure 26: MCA Parameters dialog provides a spreadsheet-like interface for viewing and editing the modifiable MCA parameters. Clicking the Send to MCA *button causes the entire parameter array to be written to the volatile memory (RAM) of the MCA, replacing the current parameter array there. Committing parameters to non-volatile memory requires another step:* Memorize MCA parameters.

The MCA parameters are arranged in an array of 128 integer values (Appendix C), so that the entire set of parameters may be transferred easily from the MCA firmware to the host software, as well as from the host software to the MCA firmware. In the MCA firmware, the array entries are indexed from 0 to 127, the first parameter in the array having the index of 0 and the last parameter having index 127.

The entire parameter array is transferred to the MCA firmware when the *Send to MCA* button is pressed in the MCA Parameters dialog (Figure 26). These parameters are written to volatile memory (RAM) so that they can be used by the MCA but not be permanent. The parameter changes will be forgotten by a soft reset or loss of power to the MCA. Note that the parameter changes might not show up in the Run mode configuration menus without reading them from the MCA. To reread the MCA parameters select the *Disconnect* menu item (without disconnecting the USB cable), followed by *Connect* to reload the parameters from the firmware. The menus will then be properly updated.

Firmware Version

The first three items in the parameters array denote the firmware version. These parameters should not be changed by the user, and so are not made available for modification in the MCA Parameters dialog. The dialog displays the parameter with index 3 in the top cell. The parameter with index 3 is the *Divisor for integral to channel.* For a complete list of parameters in the array, along with indexing, see Appendix C.

Modifying the MCA firmware version numbers would make getting support and repairs difficult, since it would not be clear what build is actually installed on the hardware. Furthermore, changing the version numbers will cause a factory restore of all parameters on the next reset or power-on of the MCA. The restored parameters may over-write the FRAM memory in some versions of the firmware, such that all of the user's parameter changes will be permanently lost.

Divisor for Integral to Channel

The divisor for converting the integral of the pulse signal to its channel number provides a coarse calibration of how gamma energy will be binned for counting. The divisor cannot provide accurate channel placement over a wide range of energies and temperatures, due to the complexities of the scintillation material and SiPMs. The pulse threshold, bias voltage, and energy correction settings also play an important role in final channel placement. For detailed discussion, see the Calibrations section.

Because the divisor scales the pulse integral, it effectively sets the channel width in terms of how much energy is represented by one channel. For example, suppose that the divisor is fixed at 200 and, after temperature stabilization, this places the photopeak for Cs-137 (662 keV) at channel 662. Then the channel width is roughly 1 keV, assuming scintillation light yield was proportional to deposited energy. Since temperature stabilization is designed to keep the pulse integral constant, stabilization is not affected by changing the divisor. Setting the divisor to 100 would reduce the channel width to 0.5 keV and place the 662 keV photopeak at channel 1323, while temperature stabilization continues to hold it there. The other calibrations for energy correction and pulse pileup rejection would need to be redone as after changing the divisor, because these calibrations depend on the channel locations of the peaks.

<< ***Changing the divisor invalidates energy correction and pulse pileup rejection*** >>

Detector Index in Array

This parameter defines the position of the detector when multiple devices are combined into a sensor array to provide additional capabilities, such as estimating the direction of the source of gamma radiation. This parameter is not used in standalone operation, nor should it be changed by the user in most circumstances. Each detector in the array must be given a unique index to support proper weighting in the direction calculation. The index is between 1 and the maximum array size, typically 32 detectors. The maximum number is programmed into the firmware and so is not modifiable by the user.

Moving Spectrum

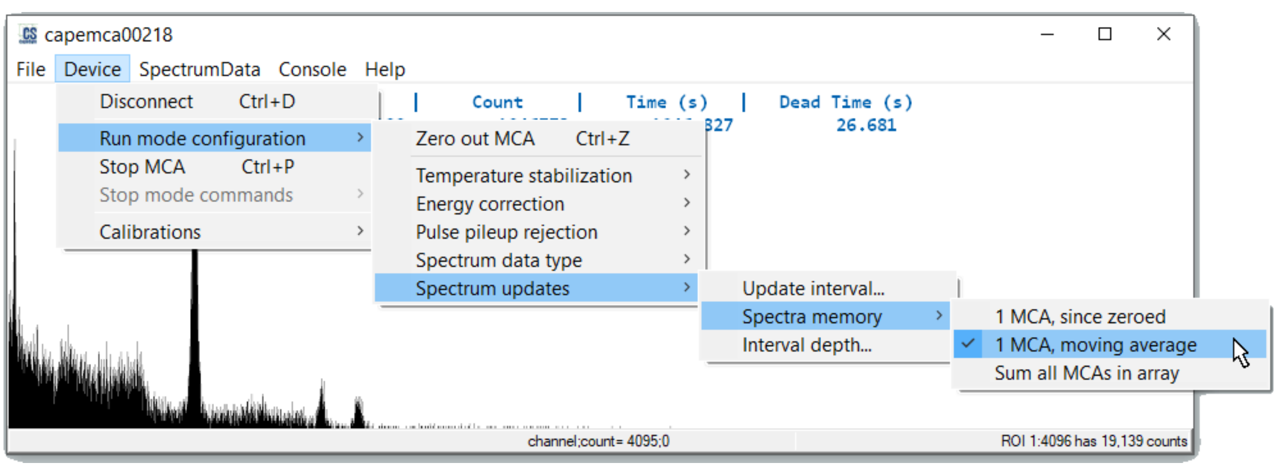


Figure 27: Turn on the Moving spectrum operation from the Spectrum updates *menu in the Run mode configuration by selecting the* 1 MCA, moving average *menu item. Equivalently, the Move spectrum parameter can be set to 1 in the Update MCA Parameters dialog (see Figure 26).*

Normally, the MCA is continuously accruing counts in the spectrum, retaining all old information until a zero out command is received. When the detector is moving, it may be helpful to forget old pulses and retain only the most recent ones. This can be done automatically by turning on *Moving spectrum* operation (Figure 27). When moving spectra are enabled the MCA is said to be in *tracking* mode.

The pulse sample, pulse list, and pulse width types of spectra should not be used when the MCA is configured to produce a moving spectrum, because the moving spectrum is computed by summing the channel values from several spectra obtained in sequential intervals. Summation is only meaningful for pulse counts, not for pulse width or pulse sample data.

<< Only the pulse count spectrum is intended to be used as a moving spectrum >>

Each output spectrum will be the sum of the most recent spectra acquired during sequential communication intervals. The number of spectra retained is given by the depth of moving spectra parameter. For example, with the communication interval set to 1 s, and the depth of spectra set to 32, each spectrum received from the MCA will be the sum of the last 32 seconds of radiation. During the next interval, a fresh spectrum will be acquired for 1 s, and then added to retained spectra while the oldest spectrum is forgotten.

When the depth of moving spectra is set to 0 or 1, only the data acquired since the previous communication interval is returned by the MCA. When depth is 0, nothing is stored in memory and all of the moving spectra memory is zeroed out each interval. When depth is 1, memory is not cleared but is instead overwritten by the recently acquired data. When depth is 2, the sum of two spectra from the last two intervals is returned. The maximum number retained is determined by the amount of RAM in the MCA, typically limited to 16, 20 or 32 spectra.

The moving spectrum calculation requires extra time for the summation of all of the channels in all of the spectra. With a depth of 32, this calculation may add an additional 8.4 ms to the communication time. This time can be minimized by using a shorter depth with a longer communication interval. For example, setting depth to 8 and communication interval to 40 (4 s) will give 32 seconds of moving spectra but take only 2 ms to calculate. Thus, only 2 ms is added to the time for host communication, rather than 8.4 ms when the 1 s intervals were used.

Communication Interval

The communication interval parameter determines how often the MCA communicates with the host software, and how long an individual acquisition continues without a break for communication. The parameter is an integer that multiples 100 ms, so a value of 1 indicates a 100 ms interval, 2 is 200 ms, 10 is 1 s, 20 is 2 s, 100 is 10 s. Most versions of the firmware limit the maximum communication interval to 10 s. Care should be used when selecting such long intervals, because the MCA will be unresponsive to user commands and parameter changes for a couple of intervals after connecting. Recall that only one command will be processed per interval. So a value of 100 would make the MCA device unresponsive for at least 20 s while the initial host commands are processed after connecting. The LEDs will be mostly off during this time making it difficult to assess the state of the device.

Pulse Threshold

The pulse threshold determines the signal level for which a pulse is detectable. The threshold is applied to a moving average filter, rather than the raw signal, to reduce detection noise. Pulse integration begins when the filter rises above the threshold, and continues until it drops below the threshold, however briefly. In order to be counted as a valid pulse, the filter must remain above threshold for at least 16 samples. The pulse threshold is given in ADC levels. For 12-bit resolution, one ADC level is 4096/3300mV = 1.24 bits per mV. In other words, each bit of the digitized signal represents ~800 µV, and a threshold of 4 would be equivalent to ~3.2 mV. For 14-bit resolution, one ADC level is 16384/3300mV = 4.96 bits per mV.

<< Changing the pulse threshold will invalidate existing calibrations >>

DAC When TS Off

The high voltage bias for the SiPMs is controlled by a 12-bit digital-to-analog converter (DAC) output voltage. When the temperature stabilization is on, the DAC is automatically calculated from the current temperature of the SiPMs. The DAC parameter (index 13) determines the value to use at reset or power-up, when the temperature stabilization (TS) is not turned on. The user can control the bias voltage by turning TS off, setting this parameter, sending it to the MCA, memorizing the parameters, and then resetting the MCA. Using Start up will not work in this scenario since the parameter is only applied to the DAC after a reset.

The DAC parameter is a value from 0 to 4095 resulting in high voltage of

$$\text{High Voltage} = (0.001773)\,DAC + V_{DAC=0}$$

where the voltage for DAC=0 will vary from MCA to MCA, but should be between 25 and 25.5 V.

Min. and Max. Pulse Channel

Two parameters (index 15 and 16) specify a channel range for pulses to include when the *Spectrum data type* is set to *Pulse sample* or *Pulse list*. In addition, these minimum and maximum exclusive limits are applied to the detector array count range used for source direction calculations. Table 4 summarizes the channel range limits applied to measurement data from the MCA. To be included in the *Pulse counts* or *Pulse widths* spectrum, the channel must be within the limits of the array, which contains 4096 counting bins. In contrast, all detected pulse are included in the CPI and CPS, regardless of how big they are.

Table 4: Energy channel ranges (exclusive) used for various measurements

Measurement Data	**(0, 2^{31})**	**(0, 4096)**	**(minPulseChannel, maxPulseChannel)**
Pulse counts		●	
Pulse widths		●	
Pulse sample			●
Pulse list			●
CPI (count per interval)	●		
NPI (in-box count per interval)		●	
CPS (packet0)	●		
CountInRangeArray (packet0)			●
(x,y,z) Direction (packet0)			●

Peak Target for DAC Servo

In the most recent MCA firmware (see Table 0), this parameter activates autonomous recording of the DAC versus temperature relationship for peak stabilization. No host computer is needed for this recording to take place, so recording can be easily done in any test environment. Recorded data is stored in non-volatile memory, so the MCA may be turned off/on during the recording process. Once sufficient data has been collected, the recorded data may be retrieved by the host computer and used to calculate the parameters for temperature stabilization, as detailed further in the Calibrations section. Data retrieval is triggered by the *Calibrations > Temperature stabilization > Fit peak servo data* menu item in Run mode. The menu item will be grayed out in Stop mode. If the menu item is grayed out in Run mode, then the MCA hardware does not support the DAC servo operation.

The peak target parameter specifies the desired channel location of one photopeak of the energy spectrum. So the MCA must be generating an energy spectrum with moving spectrum mode turned on. The frequency of DAC adjustments will be determined by the depth of the moving spectrum and the communication interval. The combined effect of depth and interval must produce a peak at least 20 counts high, and the starting peak location must be within 12% of the target. Only a single peak should be present within the ±12% range to the target location. Meeting these requirements, the MCA will automatically adjust the DAC to move the peak to the target.

The servo makes one DAC adjustment every time the full depth of the moving spectrum has been updated. For example, if the depth is 16 and the communication interval 1s, then the DAC is adjusted every 16 seconds. The size of the adjustment is proportional to the error between peak and target. If the peak is already at the target when calculating the adjustment, then the DAC value will be recorded in FRAM for the current temperature.

The peak target parameter can only be adjusted via the Update MCA Parameters dialog. When the peak target parameter is set to zero, the DAC servo will be disabled. The servo will also be disabled if temperature stabilization is turned on, or moving spectrum is turned off. When the peak target is set to -1, all of the recorded data in FRAM will be zeroed out. Make sure any recorded data has been retrieved before setting peak target to -1. To save the recorded data, first use *Calibrations > Temperature stabilization > Fit peak servo data* to retrieve it, then use *Console > DAC vs temp to console* to display it so the data can be copied from the console.

Watchdog Reset

The MCA is designed to operate continuously for a long time without supervision, but if something goes wrong the MCA could conceivably halt until it is manually reset. Some versions of the firmware (Table 0) provide a watchdog that allows the MCA to automatically reset itself if it fails to cycle through its main loop in ~16s. This watchdog reset allows the MCA to automatically resume operating after something goes wrong, but any acquired data or parameter changes in RAM will be erased during re-initialization. When implemented, the watchdog reset may enabled or disabled through the corresponding parameter (index 22). If the firmware does not support watchdog resets, changing the parameter will have no effect.

Decay Rate and Filter Width

Parameters 23 and 24 allow the user to modify the shape of the pulse processing filters in some of the newer MCAs. The two parameters are available in firmware versions 1.4.1 and higher (see Table 0). Older firmware in which filter width is fixed, do not support the use of these parameters so they are ignored.

The filter width parameter specifies the number of consecutive samples that contribute to the filter's response. The triangular filter peaks at half of the filter width in response to a step input. Hence, the filter width parameter must be an even number between 4 and 128, inclusive, which is enforced by the MCA when reading the parameters into RAM. The decay rate parameter compensates for the slow decay of pulses, and produces triangular output pulses of constant width over a broad range of deposited energy. Proper tuning leads to shorter pulses, reducing deadtime and pileups. Instructions for tuning the parameters are given in the **Calibrations** section. Deadtime corrections enabled by constant width pulses are discussed further in the **Counting Statistics** section.

Log Monitor

Some devices may contain a separate voltage signal that provides logarithmic measurement of the steady-state current through the biased detector. This voltage signal is separate from (but related to) the signal used for pulse processing.

When the linear relationship between the log (base 10) of the bias current and this voltage signal has been calibrated, parameters 25 and 26 will be positive integers representing the coefficients of the linear fit that allows the bias current to be computed from the voltage signal, as follows.

The analog voltage signal v is digitized to 12-bit number u such that it can be recovered by

$$v = 3.3 \frac{u}{4096}$$

If x is the log of the bias current, then

$$\text{bias current} = 10^x$$

and the voltage signal v will be linear with respect to x.

$$v = m\,x + b$$

The firmware estimates the bias current in nanoamps given v and these two parameters in the form:

$$p_{25} = floor\left(10^5 m\right)$$

$$p_{26} = floor\left(10^5 b\right)$$

If the parameters are uncalibrated (≤ 0), feedback is u in ADC units, rather than bias current in nanoamps.

Memorize MCA Parameters

Some of the parameters will only become active after a soft reset or power on/off of the MCA. In this case, the entire parameter array must be committed to non-volatile memory BEFORE any reset, by using *Memorize MCA parameters* from the Stop mode commands menu. Once parameters are memorized, they will be automatically loaded into RAM for use after any type of reset.

Recall MCA Parameters

The user may also request that the memorized parameters in the MCA be restored into RAM by issuing the *Recall MCA parameters* command in Stop mode (see Figure 13). This command may be used to erase the parameter changes made by the *Send to MCA* button, although power off would do that just as well.

Factory Settings Restore

The MCA firmware has a backup of the original parameters stored in flash memory. These can be copied into the volatile RAM by using *Factory settings > Restore*. To make the restoration permanent, follow up with *Memorize MCA parameters* to copy them to FRAM non-volatile memory where the user parameters are stored. A factory restore will wipe out any calibrations that were done after the original programming, so the restored settings should be thoroughly tested before overwriting FRAM memory.

The MCA parameters after factory restore will be unknown to the host software, because they have not been transferred to the host yet. If you open the MCA Parameters dialog immediately after factory restore the old parameters will be displayed. To see the restored parameters, return to Run mode, then use the Disconnect item from the Device menu to break the USB connection, followed by Connect to reestablish the connection. The restored parameters which are active in RAM will then be transferred to the host software and displayed in the MCA Parameters dialog the next time it is opened.

Soft Reset of MCA

A soft reset will reboot the MCA microcontroller while power is maintained. The microcontroller goes through its full initialization, which includes initializing all of the peripherals, reloading the memorized parameters, and zeroing out the spectrum and packet0 data. Any parameter changes that have not been memorized will be over-written. The USB connection will be broken and the WINUSB device driver restarted in the PC. The USB connection can be reestablished from the Device menu by selecting the *Connect* menu item.

Exit to Bootloader

While in Stop mode, the MCA hardware can be put into full programming mode through the menu item *Exit to bootloader*. This command causes the STM32 WINUSB device driver to be closed on the host computer, and causes the DFU device driver to become operative in its place. The STM32 bootloader will be running on the MCA, which allows the entire firmware of the MCA to rewritten, as discussed further in Appendix A. To restore MCA firmware operation after *Exit to bootloader*, the device must be completely powered off by unplugging the USB cable.

The bootloader can be used to upgrade the firmware in some instances, but this should be done only by experienced technicians. If the bootloader is used carelessly, the MCA can be completely destroyed. Note that, after the MCA has been sealed into its case,

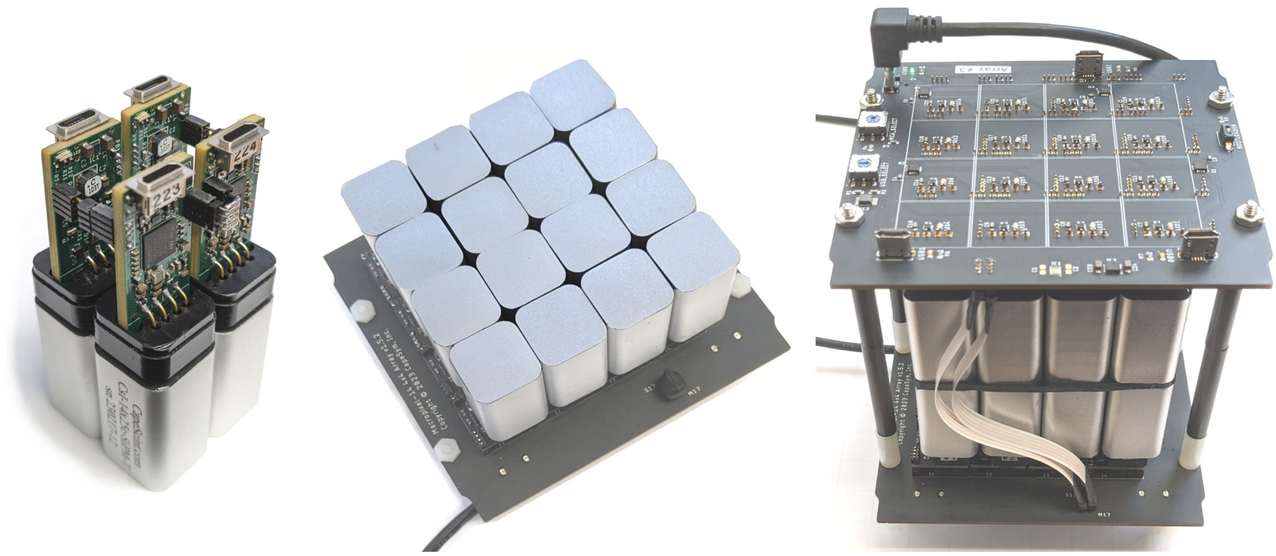
access to the bootloader becomes impossible if the existing firmware is damaged or erased!

MCA Arrays

Some types of MCAs are designed to work together to improve performance. The larger volume of the combined detectors provides increased gamma sensitivity. If all MCAs are accurately calibrated, such that the same gamma energy is mapped to the same channel, then the entire array can maintain a gamma energy resolution comparable to that of each individual detector but at the much higher total pulse rate. An array is also be able to estimate the direction of a localized source of radioactivity through the self-shielding effect. However, source direction is not possible with fewer than four detectors.

In an array, each detector is read out by its own MCA. Each detector and MCA pair is a complete gamma energy spectrometer. Combining spectra from all detectors in the array is enabled by MCA-to-MCA communication links, provided by cables between MCAs or by a backplane with embedded interconnects.

In the non-backplane configuration, the MCAs can be operated independently by connecting a standard USB cable to each one, one at a time. The host computer may then talk to each MCA via a separate instance of the host software (Figure 28). To establish standalone operation of each MCA, USB power should not be applied to another MCA until the prior MCA is already operating in standalone mode, with its LED blinking yellow instead of green.



To operate in array mode (Figure 29), every MCA in the array must receive power simultaneously, either from a non-standard USB cable, or from a *backplane* designed to distribute power to the MCAs. One, and only one, MCA must also receive a full USB data connection to the host computer, the other MCAs must receive only power from the USB plug. The USB data lines on any power-only USB cables must be unconnected; they cannot be shorted together. Each MCA uses the absence or presence of USB data line connections to determine its role in MCA-to-MCA communications.

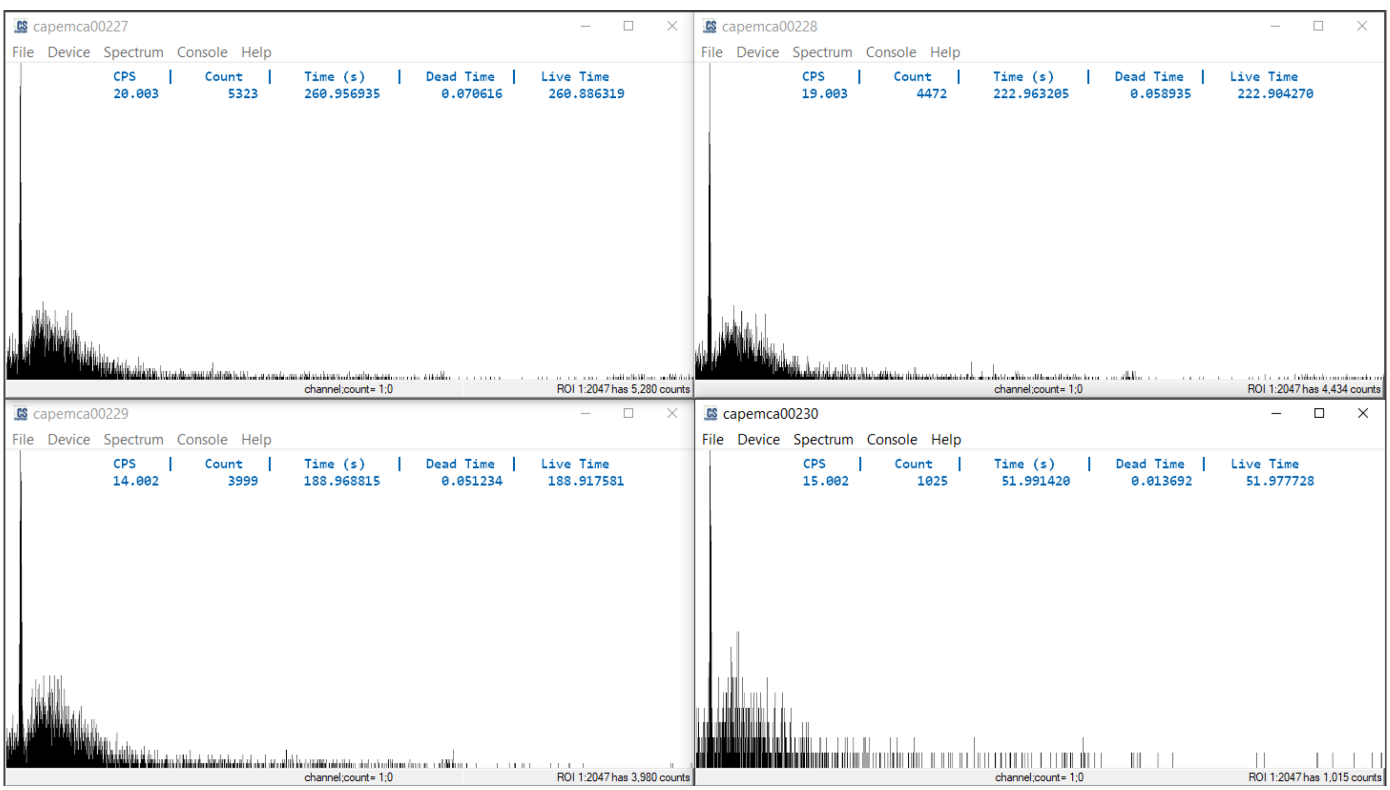


Figure 28: Four separate host software connections to the MCAs of a 2x2 array, each one operating in standalone mode. The MCAs were powered-on one at time, as can be seen by comparing the live times of standalone operation. Each spectrum comes from just one MCA.

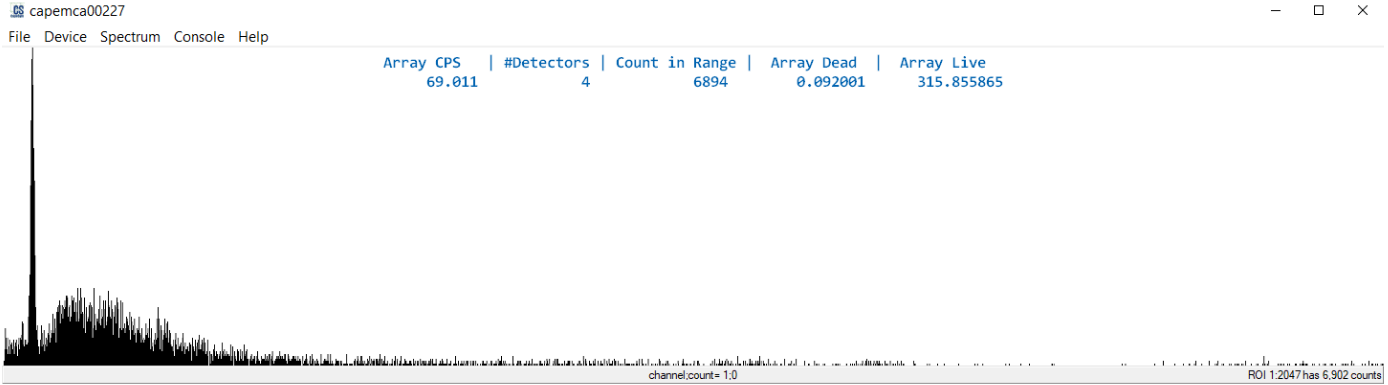
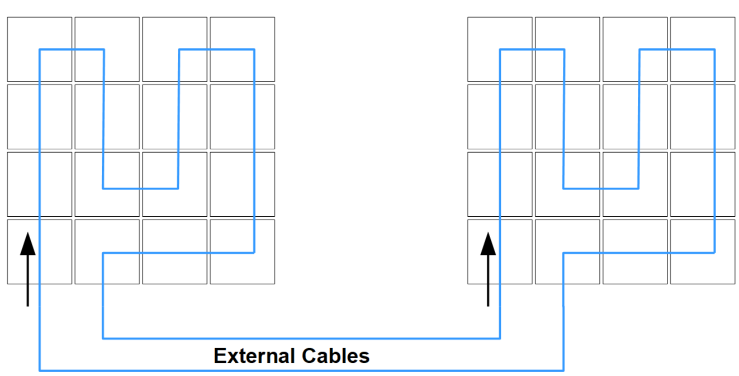


Figure 29: Array operation of the four MCAs shown in the previous figure. The MCAs were powered-on simultaneously, with a single host connection from capemca00227. The spectrum is therefore the combined result of adding together the four spectra of the individual detectors.

Which MCA is connected to the host computer is arbitrary, since all are fully capable. Every MCA in the array is running the same firmware. To change which MCA is connected to the host via USB, turn the array off, switch the USB connection, then turn the entire array back on to restart the array initialization process. The current firmware supports arrays of even numbers of detectors, up to 32 in two 4x4 layers. Any arrangement of detectors is possible, but to support directional sensing the MCAs must be placed in a predefined, tightly-packed configuration, with the detector indexes of the MCAs in a particular order (see below). Rearrangement of the MCAs or loose spacing of the detectors will invalidate the direction information computed by the array. To enable direction sensing in three dimensions, the array must consist of two layers with a minimum of four detectors in each layer.

Array Data Packets

MCA-to-MCA communications are enabled by two Serial Peripheral Interface (SPI) connections from each MCA, one to each of its two neighbors in a circular daisy chain. Each connection is a 4-wire link supporting the full duplex {$\overline{\text{SS}}$,MOSI,MISO,SCLK} SPI protocol. Each MCA is master of one link and slave of the other. The daisy chain is formed by connecting the master side of one MCA to the slave side of its neighbor, all the way around the array until the head is connected to the tail. The entire array must be daisy-chained, by a backplane or cables or some combination of cables and backplanes.



Data moves around the SPI daisy chain in both directions simultaneously. This limits the number of required data transfers to half the number of MCAs in the array. For example, in an array of 32 detectors every MCA gets a complete copy of every other MCA's data after just 16 data transfers across all the SPI links. Since there is always an even number of MCAs, the final data that an MCA receives from the clockwise direction is identical to the final data it receives from the counterclockwise direction. This fact allows every MCA to perform a data integrity test by comparing the final two receptions.

Two types of data sets are transferred over the MCA-to-MCA communication link, one containing the packet0 information and the other containing the full spectrum. The spectrum transfer only happens when the moving spectrum parameter is set to two. It is not possible to share spectra across the array while also using the moving spectrum (=1) feature, because both of these features use the same memory bank inside the MCA. Another reason to disable the array spectrum transfer (by setting the moving spectrum parameter to 0 or 1) is to eliminate the communication time overhead. Each spectrum transfer is 16384 bytes and at the SPI data rate of 8 Mbit/s it takes about 16ms to transfer those bytes from one MCA to the next one. For a 32-detector array the required 16 sequential transfers would therefore require 256ms. Thus, more than 1¼ seconds would pass for every second of acquisition time, when a 1-second update interval is used.

The packet0 related data is only 64 bytes, so it is always transferred around the array each communication interval. This data packet contains a summary of the radioactivity observed by each MCA, including the counts per second in the last interval, total pulse count, total dead and live times, and the directional information. Note that the total dead and live times reported to the host in packet0 are the sum of the dead and live times of the individual MCAs in the array, with the live time being the data acquisition time minus the dead time. The data acquisition time is when the ADC is actually sampling the detector signal.

The 64-byte data packet also forwards a subset of the commands and parameters from the host computer to all MCAs in the array. Table 5 lists the valid commands and parameters that can be applied to an entire array. If the host computer issues one of these two-byte commands to the hosted MCA, it will be forwarded to other MCAs for immediate action. Certain parameters must be consistent across the array for proper operation, and these parameters with index {9,10,11,15,16} are automatically sent in every data packet transfer, whether there is a change by the host or not. Changing one of these parameters in the hosted MCA will result in the change propagating through the array. In general, parameters which can only be changed in stop mode are NOT propagated through the array.

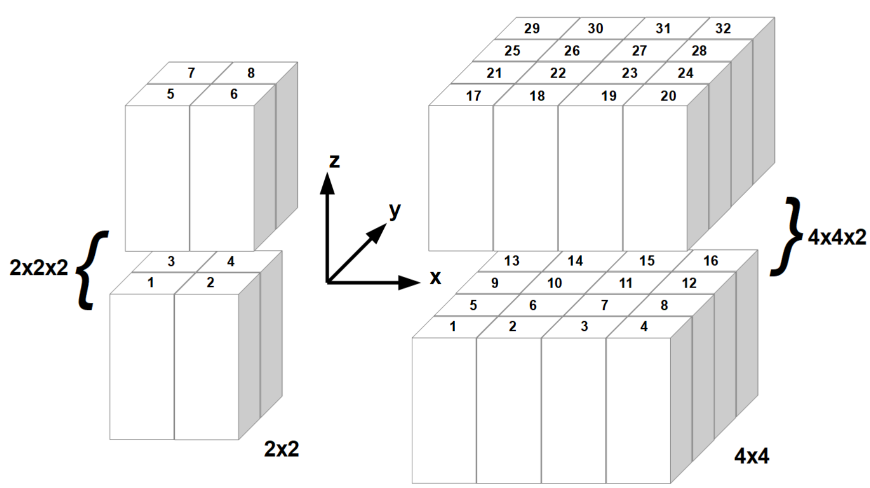
Some run mode commands are propagated through the array by using the [i,v] command, where i is the index of the parameter to modify (between 3 and 32) and v is new value. Parameters not explicitly listed in the table should be not be changed by this command. For example, issuing the [8,1] command would overwrite detector indexes throughout the array, invalidating all directional sensing capabilities.

Directional sensing is based on the total count in the range between the minimum channel and maximum channel parameters. In the self-shielding effect, each detector receives a different amount of gamma radiation due to its position in the array relative to the source of radioactivity. Each MCA independently records a spectrum from its detector and extracts the total count in the range. These values are then sent through the array data packets so that every MCA gets a copy of the count in range from every other detector. The pattern of these counts across the array are then used to determine the location of the source, using a projection matrix optimized for the type of detectors and their known positions in the array. Thus, the directional calculation can only be performed when the spectrum type is pulse counts per channel.

Table 5: Valid array-wide commands and parameter changes

Cmd	Index: Parameter(s)	Local Action Taken by Each MCA
1,1	none	Zero spectrum, packet0 and moving spectrum (if enabled)
i,v	i: See below	RAM parameter[i] set to value v (v<256)
	4: Pileup rejection	Turns on/off the use of pulse width limits
	5: Temp. stabilization	Turns on/off temperature stabilization
	6: Spectrum type	0=pulse counts, 1=pulse widths, 2=pulse sample, 3=pulse list
	7: Energy correction	Turns on/off energy correction
	9: Moving spectrum	0=no sharing, 1=locally moving, 2=spectrum sharing
	10: Depth of moving	Only applicable when moving spectrum is 1
	11: Comm. interval	Communication interval as multiple of 100ms
none	9: Moving spectrum	0=no sharing, 1=locally moving, 2=spectrum sharing
none	10: Depth of moving	Only applicable when moving spectrum is 1
none	11: Comm. interval	Communication interval as multiple of 100ms
none	15: Min. channel range	Lower bound of pulse samples, lists, and directional counts
none	16: Max. channel range	Upper bound of pulse samples, lists, and directional counts

Directional sensing requires the detector indexes are positioned in as specific way, as shown in the figure below for 2x2x2 and 4x4x2 arrays, with detector front-ends (opposite the MCA connector end) facing each other in the middle of the sandwich. A smaller array capable of only two dimensional sensing is created by using just the first layer (2x2 or 4x4) of the three dimensional arrangement. The projection matrix to implement the direction calculation for a given arrangement of detectors is typically calculated off-line using Monte Carlo simulations. The matrix is then programmed into the firmware when the array is built and is not modifiable by the user. To work correctly, the detector indexes must be arranged as shown.



When spectrum sharing is turned on (i.e. moving spectrum parameter is 2), every MCA receives a copy of the spectrum from every other MCA in the array. These spectra are combined within the MCA by the procedure listed in Table 6. For instance, when the spectrum type is pulse counts, the spectra are combined by adding the counts channel-by-channel so that the combined spectrum has counts that are the sum of the individual spectra counts. The combined spectrum is the one sent to the host in response to a data request. The host software should be configured to request both the 4096-channel spectrum and packet0, to receive all of the available array information.

Note that spectrum[0] always contains just the local information from the hosted MCA. Counts and temperatures in spectrum[0] are the same values as would be received in standalone mode. The spectrum[0] information from the other MCAs is not available to the host computer.

Table 6: How shared spectra are combined based on spectrum type

Type	**Spectrum Data**	**Method of Combining Two Spectra**
0	Pulse counts/channel	Channel-by-channel summation
1	Pulse widths/channel	Keep one non-zero pulse width per channel
2	ADC signal/sample	Keep largest value per sample
3	Pulse list	Append lists until run out of space (at 2047 pulses)
4	Pulse counts/channel	Channel-by-channel summation
6	Interarrival times	Time-bin-by-time-bin summation

Meaning of Array Lights

To power up an array, the same power source must be applied to all MCAs at the same time. For arrays configured on a single backplanes, or with built-in power+data interconnections, all MCAs are powered up simultaneously. For other configurations, additional power-only USB cables must be provided that all get switched together, e.g. through a USB hub with a power-on switch.

At power up each MCA initializes its clocks and then pauses for 0.5 seconds to ensure that any USB data lines get fully connected. Each MCA shows a yellow or blue indicator light during this phase, which is followed by the attempt to detect USB data lines. The MCA which detects the USB data connection displays green, while the other MCAs display red to signal that no data lines are present. The array then attempts to synchronize via the SPI communication links, waiting up to 3.5 seconds for all MCAs to connect.

The MCA with the host connection will be the initiator of the synchronization signal. Each MCA in the daisy chain passes the signal along, until it gets back to the hosted MCA. If this initial synchronization attempt times out after 3.5 seconds, e.g. due to a broken SPI daisy chain or an unpowered MCA, then all MCAs in the array switch to standalone mode. Any further attempt at MCA-to-MCA communication is abandoned until the next power on sequence. All MCAs in the array will flash a non-green indicator at every communication interval when running in standalone mode. The host computer will only receive data from MCAs to which it is directly connected. The blinking lights will slowly desynchronize across the array because individual MCA clocks differ slightly in frequency.

When the initial synchronization is successful, a second timed synchronization is performed to determine how many detectors are present in the array. If this is also successful and the number of detectors is determined to be greater than one, every MCA in the array will include the MCA-to-MCA communications routines in its run loop. During the communication interval the lights on all MCAs turn green simultaneously, so blinking green lights indicate that synchronization between MCAs is maintained.

Two error conditions may be indicated by a different light pattern. If an MCA flashes red instead of green, then the data integrity test failed in that MCA. Data integrity is a local test performed by every MCA, and the red flash is the only indication that there may be a problem with SPI reliability in the current environment. The second error condition involves freeze up with all MCAs displaying green continuously. This condition may be caused by more than one MCA having a USB host connection or, more rarely, by dropped SPI data frames, leading MCA-to-MCA transfers to halt prematurely between two MCAs.

Recovery from the freeze up condition can be ensured by a power off reset to reestablish synchronization. However, there is also an internal watchdog timer that will attempt a soft reset of each MCA after about 15 seconds of freeze up. The watchdog resets the MCA automatically without user intervention. The watchdog is enabled if its parameter is non-zero on power up. Once enabled, it can only be disabled by another power-on-reset with the parameter (in nonvolatile memory) set to zero.

During array operation, synchronous green blinks should stop when the host computer puts its MCA into stop mode. In stop mode the hosted MCA will display red continuously and the other MCAs display green continuously while they wait for the stopped MCA to resynchronize. From this state it is sometimes possible to return to run mode by sending a two-byte command from host computer, e.g. by the *Start up* menu item in the CapeMCA host software. In general, ***stop mode should be avoided during array operation***. To modify parameters via stop mode commands, power up the MCA in standalone mode.

Array Calibration

Subsequent sections of this manual detail the calibrations that can be performed within an individual MCA. These calibrations must be done locally, with the MCA operating in standalone mode and connected directly to the host computer via USB. Ideally, every MCA would be calibrated prior to being assembled into an array. But if an MCA needs to the calibrated while it belongs to an array, this can be done.

To recalibrate one MCA in an array, first switch the USB host connection to that MCA. Next, the array operation must be disabled before powering it on. This can be done in a couple of ways: 1) break the SPI daisy chain by disconnecting an SPI cable, or 2) leaving one or more MCAs in the array powered off. At power up, either of these modifications will cause the initial synchronization to fail, and the powered-on MCAs will all enter standalone mode. Connecting USB data cables from the host to all MCAs should also disrupt synchronization, since all MCAs would simultaneously attempt to the master of the array and fail. After the MCAs are operating as standalone gamma spectrometers, the usual calibration procedures can be applied independently to each detector in the array, as described in the next section.

Counting Statistics

Starting with software version 1.3.9 and firmware 1.4.1, CapeMCA provides a built-in method for evaluating the accuracy of the counting statistics for any particular combination of detector, MCA, and parameter settings. This validation is done through the interarrival intervals (IAI) spectrum type and associated Calibration menu commands. Note that the accuracy of counting statistics will depend on particular hardware features, including the presence of a frequency-stable external clock, and a properly-tuned triangular filter with pulse decay compensation that yields ~constant pulse widths (see Table 0).

<< The *true count* correction is accurate when pulse widths are constant >>

Counting statistics attempt to estimate the true input count rate given the measured count rate and the so-called *deadtime* created by the radiation-induced pulses. Since the detector output signal is continuously sampled and digitized before detecting pulses, multiple input events may overlap and be detected as a single pulse. Hence, every pulse creates a deadtime in which additional pulses will not be detected. The discrete sampling interval also contributes some deadtime, but this effect is much smaller than the pulse width. As discussed in Knoll[1], the true input count rate n is related to the measured count rate m by

$$m = n e^{-n\tau}$$

When pulse width is constant, the deadtime τ is the same as the average pulse width in seconds. Knowing both m and τ allows determination of n through the method derived by Müller[2]. Here, it will be sufficient to just keep the first six terms of Müller's infinite series for the correction factor.

$$n = m\left[1 + \sum_{k=1}^{6} \left((m\tau)^k \frac{(k+1)^{k-1}}{k!}\right)\right]$$

Packet0 contains three essential measurements: the total count M, the total acquisition time A, and the total pulse time (a.k.a. deadtime) which will be denoted by D. The values m and τ, as well as the product $m\tau$, may be obtained directly from these essential measurements using the following relations.

$$m = M \div A \quad , \quad \tau = D \div M \quad , \quad m\tau = D \div A$$

Therefore, m is the average count rate over the whole measurement (since the spectrum was zeroed), and τ is average pulse width over the whole measurement. The duration in seconds of the measurement is A.

Starting in firmware version 1.4.2, the MCA includes the corrected total count and counting rate in packet0, as follows, where K_f is the Müller correction factor shown above in square brackets.

$$\text{cpsArray} = m = M \div A$$

$$\text{correctedCPSArray} = n = m \times K_f$$

$$\text{correctedTotalCountArray} = N = M \times K_f$$

For a single detector, the fact that these fields are named “array” values is irrelevant. When multiple detectors share data as an array, then these fields would carry the sum of the fields over all detectors, as expected. To complete the correspondence between packet0 fields and the counting statistics, we have

1 Knoll, G.F. (2010) Radiation Detection and Measurement. John Wiley & Sons.
2 Müller, J.W. (1984) Inversion of the Takács formula. Rapport BIPM-84/3. Bureau Intl. Poids et Mesures, F-92310 Sevres.

$$\text{totalCount} = M$$

$$\text{totalPulseTime} = D$$

$$\text{totalAcquisitionTime} = A$$

The totalAcquisitionTime field was also added in v1.4.2 firmware, to improve accuracy. In prior versions the acquisition time was computed by multiplying the usPerInterval by the totalIntervals fields. Given these changes in the packet0 fields, host software v1.3.9 higher is only compatible with v1.4.2 and higher of the MCA firmware. Users of MCAs with older firmware should stick with prior versions of the host software.

Another innovation in the newer MCAs is the ability to record interarrival intervals along with the essential measurements, allowing the accuracy of the counting statistics to be easily verified. This is done by setting the spectrum type to *Interarrival times* before the measurement is started. The middle part of the IAI distribution will then contain an accurate measurement of the true input count rate, as described by Abbene and Gerardi[3]. This count rate is determined by fitting an exponential curve to the IAI distribution at the end of the measurement, using menu command *Calibrations > Interarrival intervals (IAI) > Fit curve to IAI spectrum*, as codified in the following procedure.

True Input Count Rate Procedure

1. Establish parameter settings for constant pulse width using the *Pulse widths* spectrum
2. Fix the distance between detector and source to establish a consistent counting rate
3. Switch spectrum data type to *Interarrival times* in the *Run mode configuration* menu
4. Set *Request # of channels* in the Spectrum menu to 4096+0 to receive packet0 data
5. Zero the spectrum to start the measurement
6. When enough data are collected, use *Disconnect* to stop listening to the MCA
7. Adjust the ROI (*Spectrum > X-axis range > Set ROI*)
   i. Exclude the first 5 to 10 channels where counts are erroneous due to deadtime
   ii. Exclude last channels where low count rates (< 100) are recorded
8. Fit an exponential curve to ROI counts (*Interarrival intervals (IAI) > Fit curve to IAI spectrum*)
9. Repeat step 8 to improve R-squared by collecting more data and/or changing the ROI

When the fitted IAI curve is drawn (Figure 30), the estimated true count rate will be displayed in the main window. Details of the regression are displayed in the console, including the R-squared metric for the goodness of fit. If the R-squared value is less 0.9, the fit will fail. To collect more data, simply *Connect* to the MCA. Because the MCA continued to accumulate data while it was disconnected, the additional data will immediately appear in the main window. You may also need to adjust the ROI to exclude more of the first or last time bins to improve the fit. When the measured count rate is more than 2000 or 3000 CPS, aim for an R-squared value of at least 0.998 to improve the true count accuracy.

3 Abbene, L., Gerardi, G. (2015) Journal of Synchrotron Radiation. 22, pp. 1190–1201.

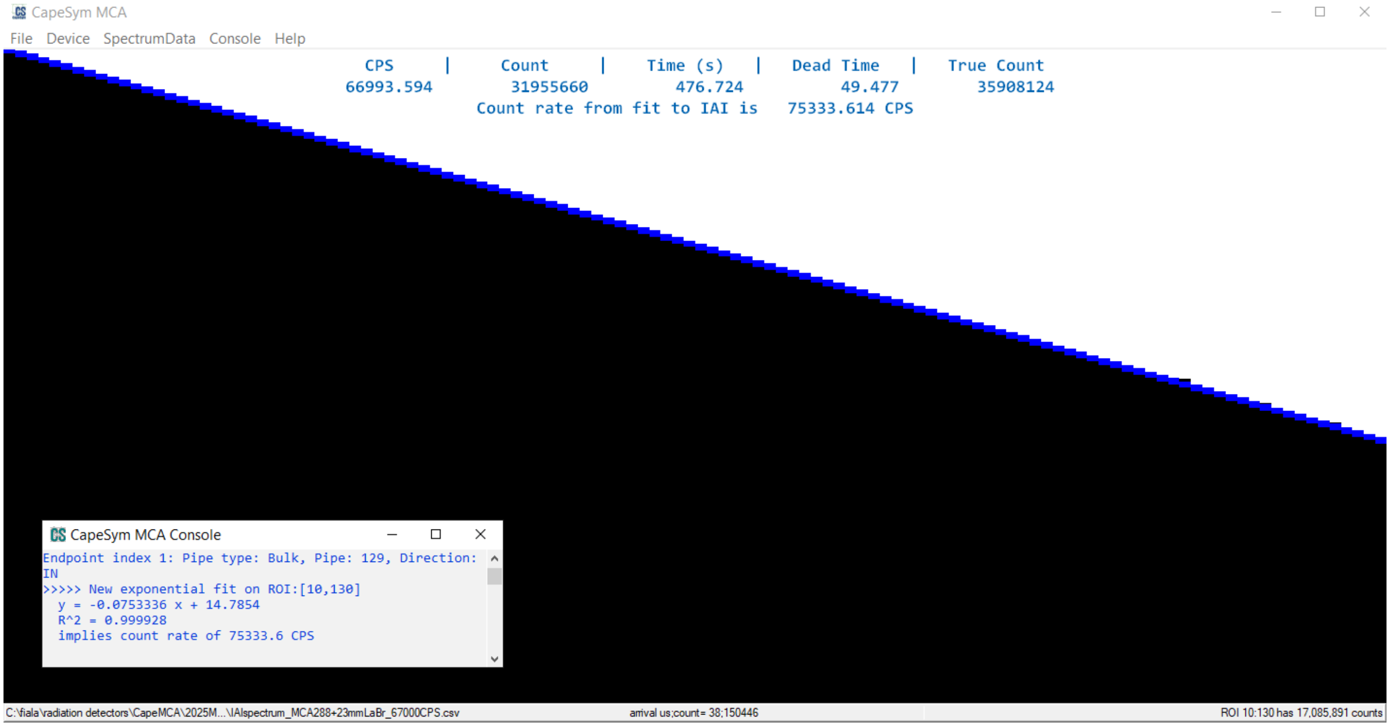


*Figure 30: Fitting an exponential curve to the recorded IAI spectrum provides a measurement of the true input count rate. Here, the y-axis is scaled by the natural logarithm so that the exponential distribution appears as a straight line. The fitted line to the scaled y values is displayed in the console (*inset*) along with the R^2 metric of 0.999928, indicating a good fit. The fitted count rate of 75,333.6 CPS confirms the true count rate provided by the MCA (35,908,124/476.724 = 75,322.6 CPS), to within 0.015%.*

Figure 30 demonstrates the validation of counting statistics using the above procedure for a $LaBr_3$ Macropixel instrumented by the most recent MCA hardware and firmware. The MCA reports that the true count is N = 35,908,124, the deadtime D = 49.477s, the acquisition time A = 476.724s, and the measured count of M = 31,955,660. By the above formulas, the measured count rate m = 67,032, the corrected count rate n = 75,323, and average pulse width τ = 1.5483μs (~15.5 samples at 10Msps). From these values we can verify the exponential relationship.

$$67032 = m = n\,e^{-n\tau} = 75323\,e^{-75323\times 1.5483\times 10^{-6}} = 67032$$

The exponential fit to the IAI spectrum then confirms that the true count rate for this measurement is 75,333.6 CPS, and shows that the accuracy of the MCA correction is within 0.015% of the measurement.

Calibrations

Attempting to re-calibrate the MCA hardware may destroy any existing calibration, so make sure that you fully understand the procedures described below before attempting operations in the Calibrations menu. There is no guarantee that the current calibration was stored in flash at the factory, so the factory reset command might not be able to restore the current calibration. To make sure you can return to an existing calibration, use the *Parameters to console* item in the Console menu to list the parameters. Copy the parameters from the console by highlighting the text with the mouse and using the Enter key to copy the highlighted text from the console to the clipboard. Then paste the parameters into a text editor such as Notepad and save the file for future reference.

When parameters are changed through the Calibrations menu (Figure 31), they are not immediately applied to the MCA – calibration parameter changes must be explicitly sent to the MCA to put them into effect. Calibration parameters can be sent to the MCA when the device is in Stop mode via the *Update MCA parameters...* menu item. This dialog also allows the new calibration parameters to be reviewed before modifying the MCA hardware.

<< Send to MCA *is necessary to put parameter changes into effect* >>

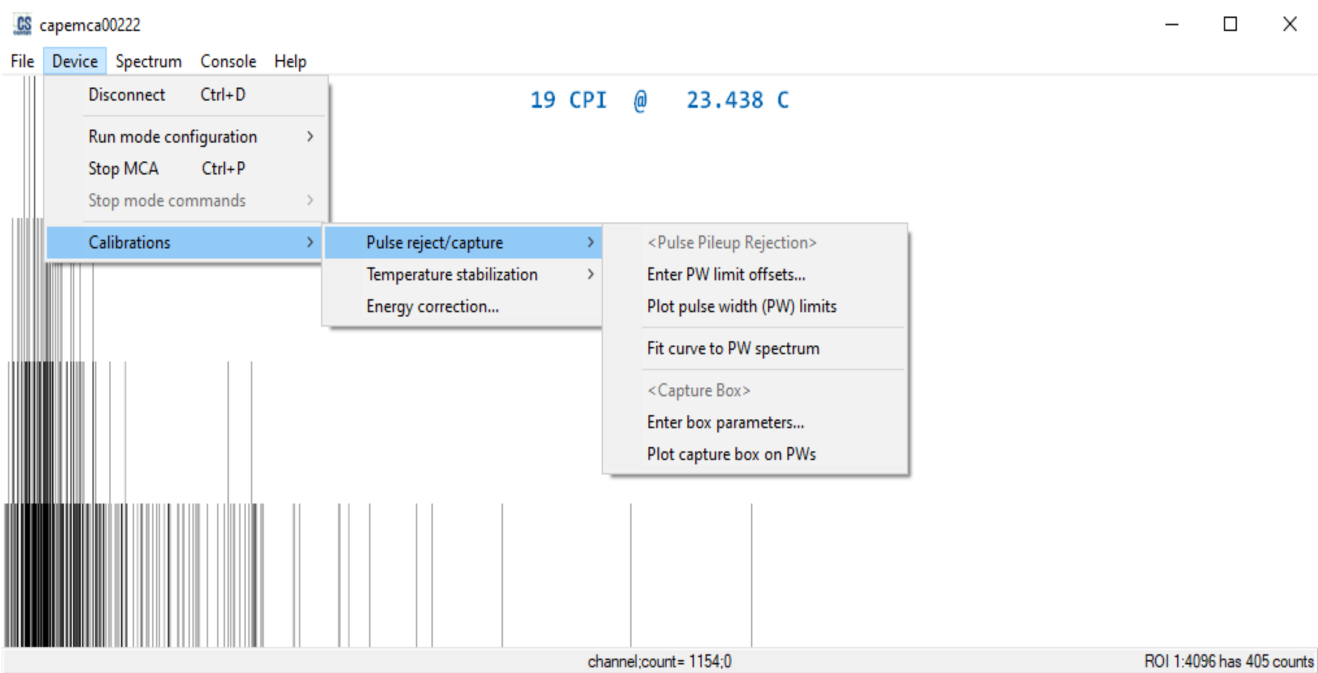


Figure 31: Calibration menu items allow the parameters used for pulse pileup rejection, capture box counting, temperature stabilization, and energy correction to be viewed and modified.

Calibration parameters are all interrelated and must be adjusted in a particular order for best results. For example, changing the pulse threshold parameter will change the pulse integral and pulse width for a given energy deposition. This change would invalidate most of the other calibrations, including temperature stabilization, energy correction, and the limits used for pulse pileup rejection. The pulse width limits should be the final step of calibration, and none of the other calibration parameters should be changed once the limits are established.

Table 7: Order of Parameter Modifications for Proper Calibration

Step	Index: Parameter(s)	Purpose
1	13: DAC value	Set default high voltage bias applied to SiPM array
2	23,24: filter width, decay rate	Configure filter to optimize performance
3	12: Pulse threshold	Remove counts caused by electronic noise
4	3: Integral divisor	Set channel for 662 keV photopeak at room °C
5	38-56: Add TS lines	Stabilization by setting DAC vs. temperature
6	57+: Energy correction	Correct channel locations of known energy peaks
7	32-37: PW limiting	Pulse pileup rejection by setting pulse width limits

<< Calibration parameters must be modified in the prescribed order !>>

The order of calibrations and the associated parameters that will be modified are given in Table 7. The entire calibration process is described in the following sections, and the full set of MCA parameters are listed in the MCA Parameters dialog and in Appendix C.

Step 1: High Voltage Bias

A reasonable default DAC level (parameter index 13) is set during the factory programming of the MCA, and can usually be restored by the *Factory settings* item in the Stop mode commands menu. However, if this programming is lost, restoring a reasonable value to this parameter would be the first order of business.

The default 12-bit DAC value needs to be near 2000, in the middle of its range of [0,4095], in order to get a reasonable high voltage bias. This bias must be 1V to 6V over the SiPM breakdown voltage of about 24.5V at room temperature. If the DAC level is zero, the bias output by the MCA will be only 25V to 25.5V, which will be insufficient for Geiger mode operation of the SiPM array. An over-voltage of about 4.5V is recommended for effective room temperature operation. Since the breakdown voltage at room temperature is not precisely known, the DAC value is typically adjusted to get ~29V for the initial bias.

Step 2: Filter Width and Decay Rate

Step 2 only applies to newer firmware that includes adjustable filter parameters. Most older MCAs having firmware v1.3.8 or lower, have fixed filter widths and no compensation for pulse decay, so that pulse widths tend to increase with deposited energy. If the filter width and decay rate parameters have initial values of -1, then these parameters are not adjustable. Users of older MCAs should skip ahead to Step 3.

A number of factors will impact the choice of filter width and decay rate parameters, including the type of scintillator, the SiPM array readout RC constant, and the sampling rate of the MCA. Subsequent calibration steps will be highly dependent on the filtering parameters, which affect both the quality of the counting statistics and the energy resolution performance. To get accurate deadtime corrections, the output pulse width must be constant over as much of the energy range as possible.

For best performance in energy resolution, the filter width should set a value that causes the triangular filter output to peak after the unfiltered pulse reaches maximum amplitude. For this reason slow scintillators will require a wider filter than faster scintillators. Figure 32 shows an example of triangular filter output overlaid on pulse samples from the fast scintillator $LaBr_3$. The filter responds to the fast rise time of a pulse with the characteristic triangular shape, but the pulse decay produces a prominent undershoot in the output of the filter. The undershoot degrades energy resolution at higher counting rates because some amount of pulse amplitude will be lost when pulses are close together.

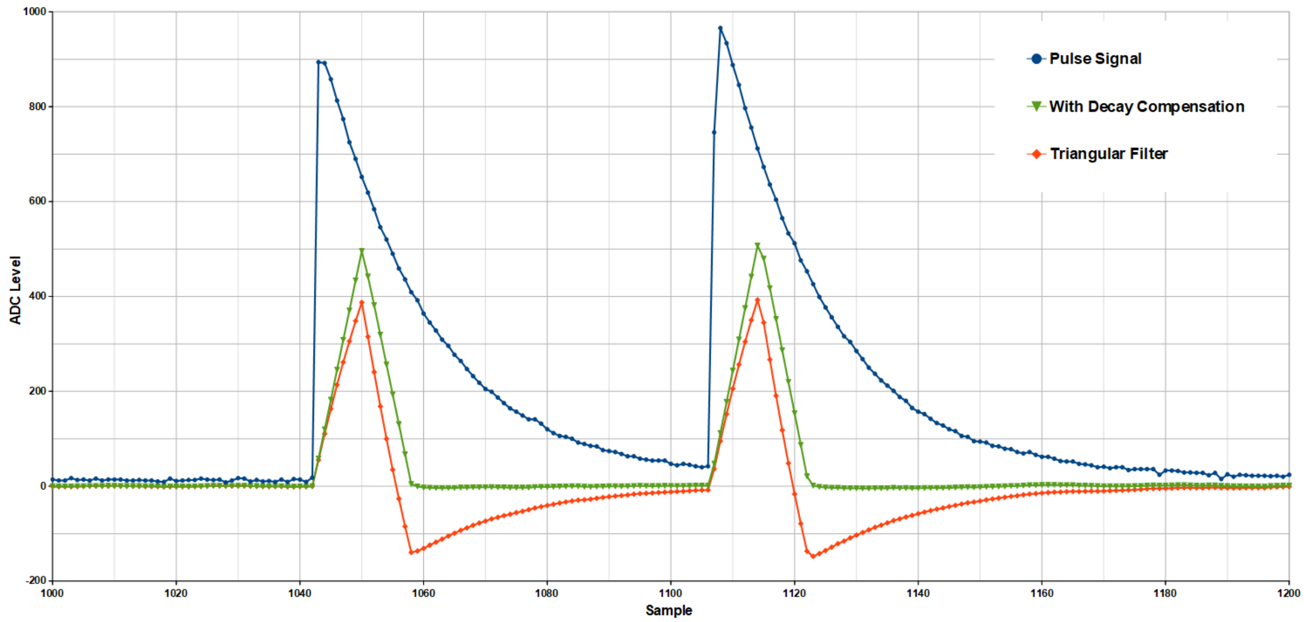


Figure 32: MCA filter outputs on two unfiltered pulses sampled at 10Msps (blue). The triangular filter without decay compensation (red) is asymmetric due to the slow pulse decay. The filter width parameter is 16, so there are 8 samples in the rising part and 8 samples in the falling part. A second filter for decay compensation (green) makes the output symmetrical when decay rate is set to 17.

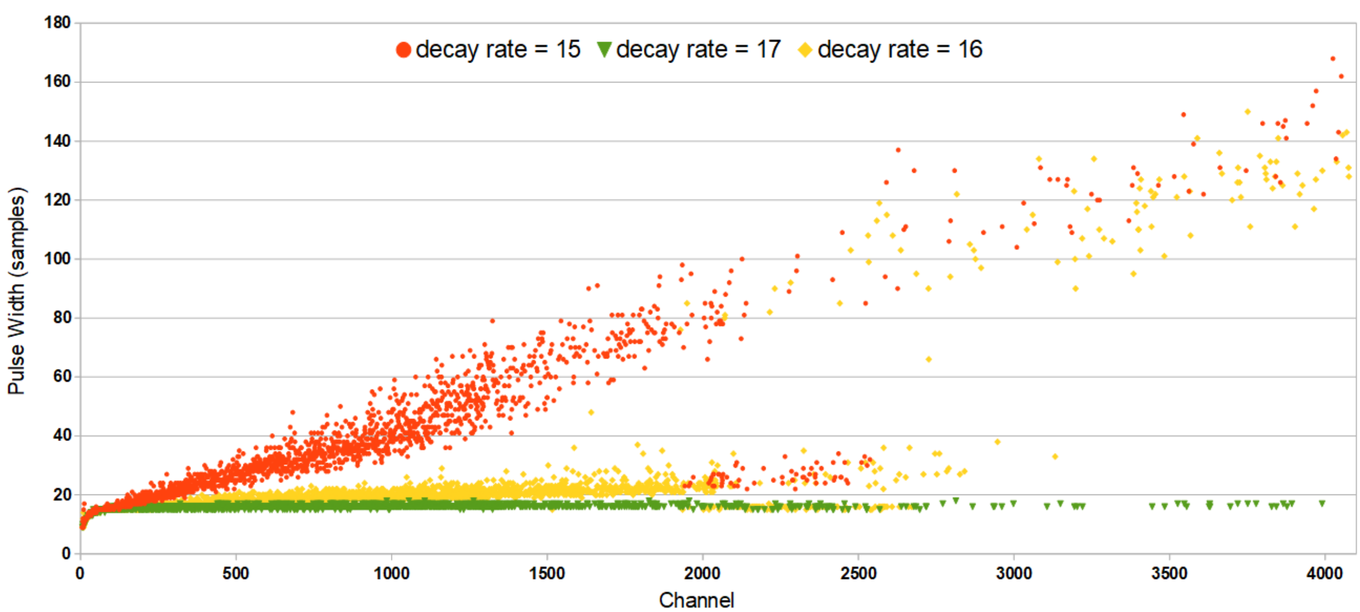


Figure 33: The proper decay rate is where pulse widths just become constant over a wide energy range (decay rate=17), as determined by observing the Pulse Width spectrum as the parameter is adjusted. The scintillator $LaBr_3$ has some faster decaying background pulses in the energy range 2000 to 2500, but with the decay rate at 17, even these pulses have the same width over all energies.

The decay rate parameter specifies a multiplier for a second integrator that compensates the pulse decay. When this parameter is set properly, the secondary output is a symmetrical triangular response with no undershoot. Figure 32 shows how the decay rate parameter affects the shape of the output. The threshold for pulse detection is applied to the output of the secondary filter. The detected pulse width is the part of the secondary filter output that is above threshold. The easiest way to observe the change in the pulse width when tuning the decay rate parameter is to use the pulse width spectrum (Figure 33). Start with a decay rate less than the filter width and gradually increase it until the pulse width spectrum flattens out and pulse widths become constant over higher energies. Be aware that increasing the decay rate too much will again produce the undershoot that degrades energy resolution.

Slow scintillators such as SrI_2 can exhibit slower pulse onset and decay than observed in fast scintillators. Therefore, slow scintillators require more filter width and decay, especially when sampling at 10 Msps. Even with the longer shaping time, it may be difficult to obtain good performance in terms of both energy resolution and counting statistics. The older firmware/hardware without adjustable filter parameters uses a box filter for pulse detection and integration of the raw signal for energy measurement. This improves energy resolution (Figure 34) but reduces the accuracy of deadtime corrections due to the variation of pulse width as a function of deposited energy.

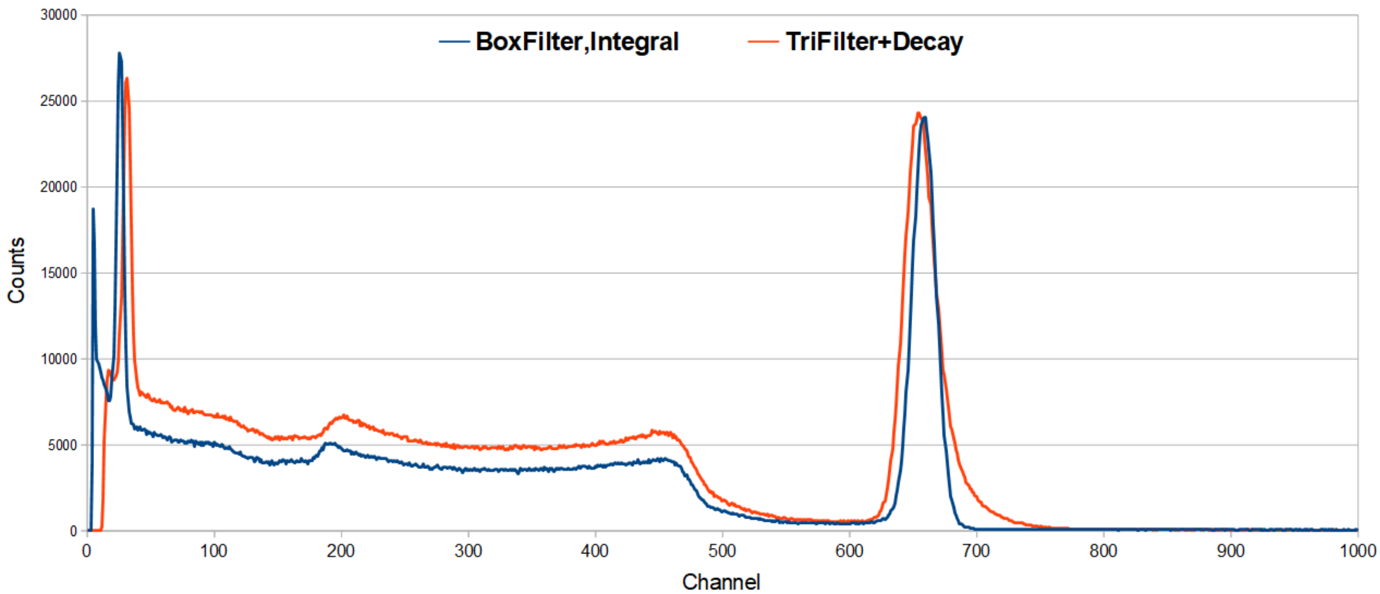


Figure 34: Comparison of the Cs-137 spectra from SrI_2 for two different types of pulse processing. Older MCAs use a box filter for pulse detection and integrate the unfiltered signal to measure energy. For slow scintillators this produces better energy resolution than triangular filtering with decay compensation.

Step 3: Pulse Threshold

The purpose of this step is to set the minimum pulse threshold to keep noise out of the low energy channels. When the pulse threshold is set too low, SiPM current fluctuations can resemble pulses causing a high count rate in the lowest channels. Because the dark current increases with temperature, the determination of the best pulse threshold may require a warming plate or environmental chamber to increase the temperature of the detector to the range of 35-40°C. A pulse threshold of 4 may be sufficient to suppress noise up to about 40°C in some cases. Higher environmental temperatures or excessive radiation damage may warrant a higher pulse threshold, although it may also be sufficient to just shift the ROI to excluded the low energy channels from the display when those channels are not relevant to the application.

Step 4: Divisor for Integral to Channel

Return the detector and MCA back to room temperature, and wait for the temperature to reach a steady state. Then expose the detector to a known radiation test source with as few energy peaks as possible. For purposes of this discussion, a Cs-137 test source will used throughout the rest of the calibration procedure. Step 4 will adjust the divisor parameter (index 3) to place the 662 keV peak at channel 662 in room temperature (about 21°C).

Divisor Adjustment Procedure

1. Device > Connect
2. Make sure temperature stabilization, energy correction, and pulse pile rejection are ***disabled***
3. Device > Run mode configuration > Zero out spectrum
4. Wait for a well-formed 662 keV photopeak to develop
5. Spectrum > Peak type = Mean
6. Click (left mouse button) on the 662 keV photopeak and note the channel location: c
7. Device > Stop MCA
8. Device > Stop mode commands > Update MCA parameters...
9. Modify the divisor parameter according to the formula: $\text{new divisor} = \text{old divisor} \times (\frac{c}{662})$
10. Press [Send to MCA] button
11. Device > Stop mode commands > Memorize MCA parameters
12. Device > Stop mode commands > Soft Reset
13. Re-Connect to the MCA and check the channel location of the 662 keV photopeak

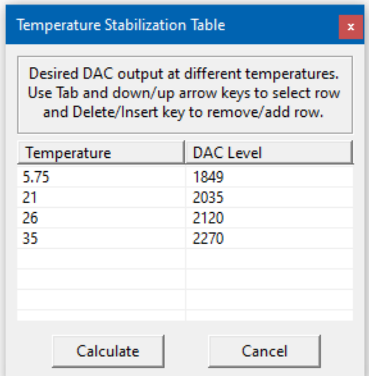
The above procedure may be repeated if the desired accuracy is not obtained, but a stable channel location will not be possible until the calibration of temperature stabilization is completed. If the temperature of the device is changing, making further changes to the divisor will be fruitless. To the greatest degree possible, the temperature should be constant during the above procedure.

Step 5: Temperature Stabilization

Temperature stabilization is done by setting the proper digital-to-analog (DAC) output to control the high voltage (HV) bias on the SiPM array. The HV bias determines how far above the breakdown voltage the SiPMs are operating, which determines the amplitude of the electrical pulse generated in response to light inside the scintillator. SiPM properties such as breakdown voltage are strongly dependent on temperature, so the bias must be adjusted as temperature changes to maintain a constant pulse amplitude. The microcontroller can do this automatically if the optimal DAC values are known for a few key temperatures.

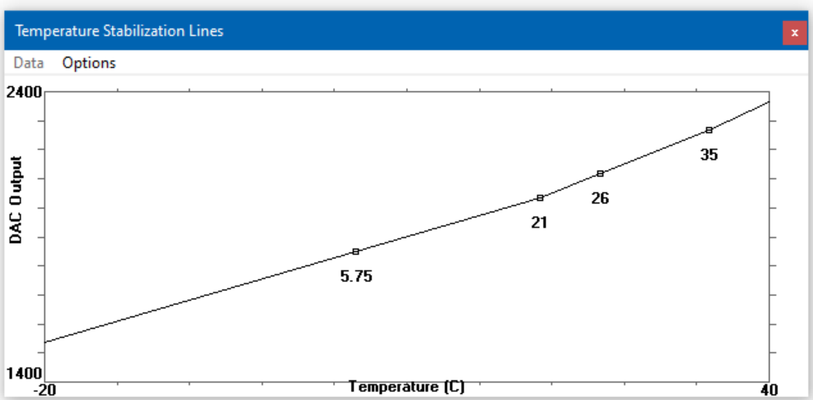
Thus, the goal of this step is to find the DAC levels that will place the 662 keV photopeak at channel 662 for specific temperatures. The microcontroller will interpolate/extrapolate linearly the DAC levels between/beyond these temperatures. Therefore, calibration requires at least two points, each point consisting of a temperature and corresponding DAC value, in order to stabilize the linear dependence of breakdown voltage on temperature. Additional points may be needed to compensate non-linear temperature dependencies, such as the increase in dark current above room temperature.

The (temperature,DAC) pairs of the calibration are listed in the Temperature Stabilization Table, accessed by Device > Calibrations > Temperature stabilization > Edit HV DAC table... These table entries are measured during the calibration procedure, and then entered by the user. The entries will then be converted to a set of MCA parameters defining the line segments for temperature stabilization. If the table is empty when the MCA is connected, then no temperature stabilization calibration has been done yet.

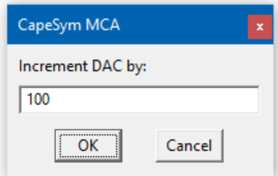


Up to seven points may be used to define the piece-wise linear relationship between DAC and temperature. However, no more than six points will be retained. The last temperature entered in the table is used to determine the slope of the extrapolation at higher temperature. The slope between the first two points in the table determine the extrapolation to lower temperature. For the minimal calibration, two points must be entered and only one point, at the lowest temperature, will be retained after the slope is calculated. This minimal calibration defines a single line for the entire temperature range.

After clicking OK in the table, the full piece-wise linear profile can be visualized by selecting Device > Calibrations > Temperature stabilization > Plot HV DAC lines..., as shown in the following figure. An accurate temperature stabilization should provide one slope at room temperature, along with different slopes in the higher and lower temperature ranges. Increased slope is needed above room temperature, and decreased slope below room temperature.



The calibration procedure involves determining the DAC value that will set the 662 keV photopeak at channel 662 for a few key temperatures. To do this the temperature stabilization, energy correction, and pulse pileup rejection should first be turned off, so that the channel location will be determined only by the HV bias on the SiPMs. To facilitate tracking the location of the photopeak while temperature is changing, it may be helpful to turn on the Moving spectrum option (Figure 25). After clicking on the 662 keV photopeak, set the Peak type to Mean in the Spectrum menu so that the center of the peak is tracked and reported above the spectrum.



The DAC output can be changed while in Run mode by using Calibrations > Temperature stabilization > Bump DAC up/down... as shown above. Just enter an integer between -100 and 100 in this dialog and hit OK to change the DAC value. Increasing the DAC by 100 will increase the HV output by about 0.177 V. The breakdown voltage dependence is about 21.5 mV per °C at room temperature, a coefficient usually specified in the SiPM datasheet. A shift of 10°C will typically shift the 662 keV photopeak location by 60 channels. So a DAC increment of 100 would shift the 662 keV peak location about 50 channels.

One method of conducting the calibration would be to maintain the detector at a fixed temperature and adjust the DAC until the 662 keV photopeak is shifted to channel 662. Then manually record the temperature and DAC value, change the temperature, and repeat the process. To get continual feedback of the current DAC level while in Run mode, set the Rate feedback type to *DAC level for HV* from the Run mode configuration menu. Once a few points have been recorded, they can be entered in the Temperature Stabilization Table. The table will compute the slopes and y-intercepts for the temperature stabilization parameters, and these parameters may then be transferred to the MCA for validation by using the MCA Parameters dialog.

The above calibration method may be difficult to apply if the temperature of the detector cannot be reliably controlled, so an alternative method is detailed below that can be used while the detector slowly warms up from freezing cold. To calibrate at temperatures significantly above room temperature, a warming plate may be required. To slow down the temperature rise for small detectors, it may be helpful to keep a larger thermal inertia, such as a chilled block of glass, in contact with the detector during warm up.

TS Calibration Setup Procedure

1. Device > Connect
2. Device > Stop MCA
3. Device > Stop mode commands > Update MCA parameters...
    i. Pulse pileup rejection = 0;
    ii. Temperature stabilization = 0
    iii. Error correction = 0
    iv. Moving spectrum = 0
    v. Communication interval = 10 (for 1 second updates)
    vi. DAC = 1700-2000 (when TS is off at reset)
    vii. Rate feedback type = 1 (DAC value and temperature)
4. Press [Send to MCA] button
5. Device > Stop mode commands > Memorize MCA parameters
6. Device > Stop mode commands > Soft Reset
7. Device > Connect
8. Console > Parameters to console
9. Console > Show console
10. Verify all of the MCA parameter settings have been set as desired

After the above procedure, the MCA and detector can be unplugged from USB power and placed in a frost-free freezer until they are well below 0°C. (The minimum operating temperature is -40°C.) Freeze the thermal inertia block to the same temperature. Keep everything frozen until ready to begin recording spectra in Step 4 of the following calibration procedure.

The goal of the following procedure is to automatically record temperature and DAC values at closely spaced temperature intervals while the DAC value is stepped through increasing values. For each DAC step, the temperature should be allowed to pass through the temperature at which the photopeak aligns with channel 662. After the photopeak moves below 662, the DAC will be incremented to the next step while recording continues. A series of (temperature,DAC) pairs can then be inferred from the recorded data to determine the values to enter into the Temperature Stabilization Table. Figure 35 illustrates the procedure.

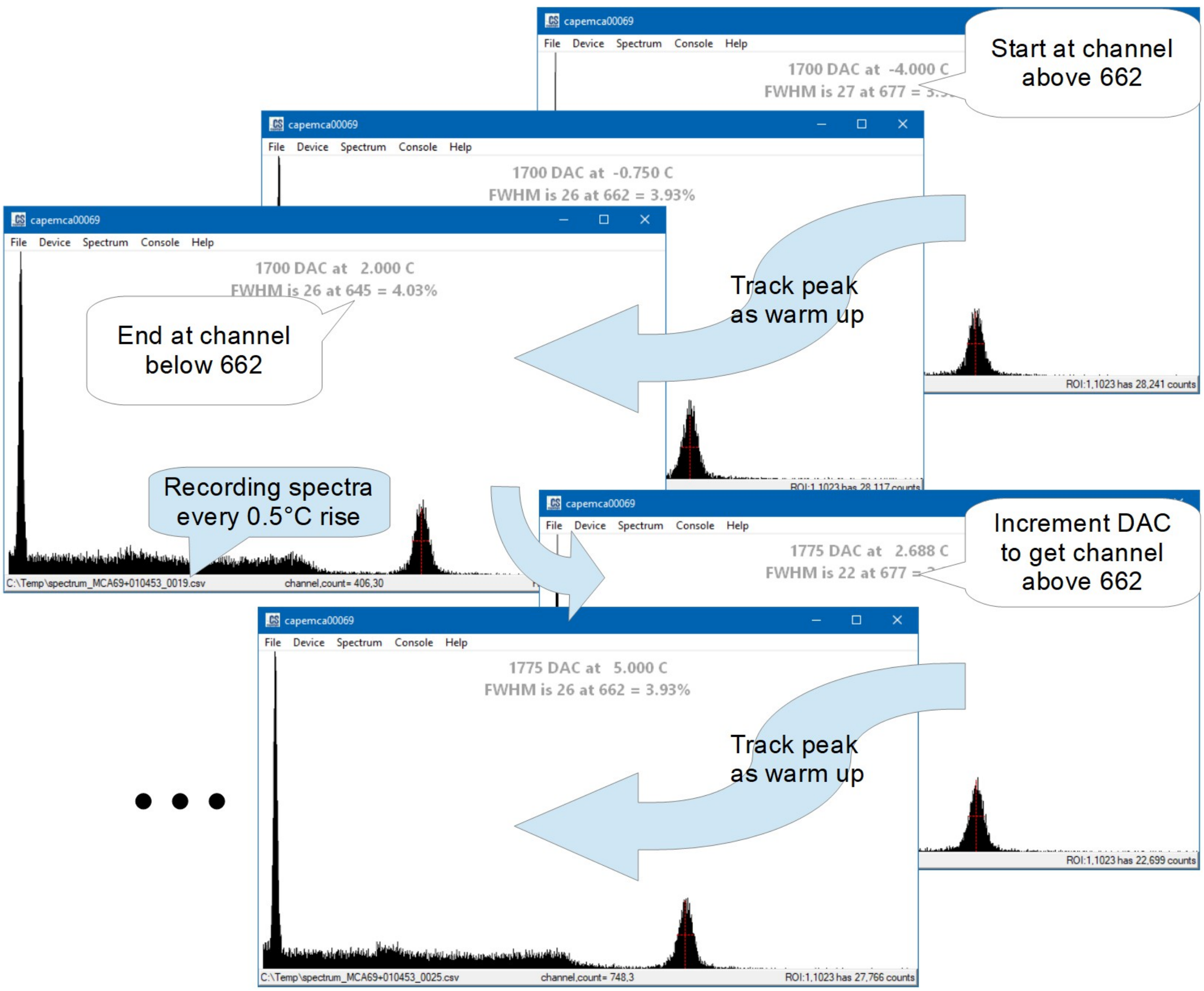


Figure 35: The TS calibration Auto Save procedure involves periodically shifting the DAC level so that the channel location of the 662 keV photopeak passes through 662 as the detector warms up. By auto-saving a spectrum at every half a degree rise in temperature, a record is made of the temperature where channel 662 is crossed for every DAC level specified.

A moving spectrum is not required during the Auto Save Procedure, because the spectrum will be zeroed out after it is recorded at each 0.5°C interval. Each spectrum will contain all of the events that occurred during each 0.5°C rise in temperature. Hence, the peak location in the spectrum will have occurred at the recorded temperature T minus half the interval width, or approximately T – 0.25°C.

TS Calibration Auto Save Procedure

1. File > Auto save...
   i. Filename: spectrum_0000.csv
   ii. Check *Encode 16-temperature with 16-bit CPS* (which will be DAC instead of CPS)
   iii. Save file at intervals of Temp. change = 0.5
   iv. Leave ENABLE AUTO SAVE unchecked for now
2. Press [OK] to keep these Auto save settings
3. Spectrum > Peak type > Mean
4. Remove the components from the freezer and place in foam insulation with the thermal inertia touching the detector. Place the Cs-137 close enough to the detector for about 500-1500 CPS
5. Plug in the USB cable.
6. Device > Connect
7. File > Auto save... to check the ENABLE AUTO SAVE and hit OK
8. Click the left mouse button while the mouse pointer is on the 662 keV photopeak
9. Device > Calibrations > Temperature stabilization > Bump DAC up/down... and increment or decrement as needed to put the photopeak about 20-30 channels above channel 662
10. Keep the DAC constant until photopeak is about 10-20 channels below channel 662
11. Device > Calibrations > Temperature stabilization > Bump DAC up/down... increment by 75
12. Device > Run mode configuration > Zero out spectrum
13. Right click on spectrum with mouse to clear the peak tracking.
14. Click left mouse button while the mouse pointer is on the 662 keV photopeak
15. Keep the DAC constant until photopeak is about 10-20 channels below channel 662
16. Repeat from steps 11-15 until the detector reaches the desired maximum temperature or
17. To continue beyond room temperature, transfer detector to warming plate, and repeat steps 11-15 until the detector reaches ~40°C
18. File > Quit autosave
19. Device > Disconnect

The entries of the Temperature Stabilization Table can now be determined from the data contained in the sequence of spectra recorded by the above procedure. This information is easily extracted using the Auto Load procedure with peak tracking turned on, as follows. The photopeak will be tracked automatically, at least until the next DAC level where there is a jump in the channel location. If this jump is too wide, tracking may fail, in which case the right and left mouse clicks will be required to clear the bad track and get tracking back on the peak. Dealing with large jumps may require increasing the display time for each load to allow this manual intervention, or by limiting the number of loads to just the spectra from a single DAC level. The following procedure assumes that the jumps are small enough to allow continuous tracking over the whole data set.

TS Calibration Auto Load Procedure

1. File > Load spectrum to load the first spectrum in the data set: spectrum_0001.csv
2. Spectrum > Peak type > Mean
3. Click on the 662 keV photopeak to begin tracking its location.
4. Spectrum > Peaks to console
5. Console > Show console
6. File > Auto load...
    1. Filename: spectrum_0001.csv
    2. Time (seconds) = 1
    3. Loop: check *Never*
    4. Check ENABLE AUTO LOAD
7. Press [OK] to begin the Auto load operation.
8. Observe that temperature and channel location is being tracked correctly and reported to the console. The sequence will stop automatically when the all files have be processed.
9. Uncheck Spectrum > Peaks to console
10. In the console, use the mouse pointer to highlight the temperature and peak location data, then press Enter to copy this data to the clipboard.
11. Open a spreadsheet and paste the data into it.

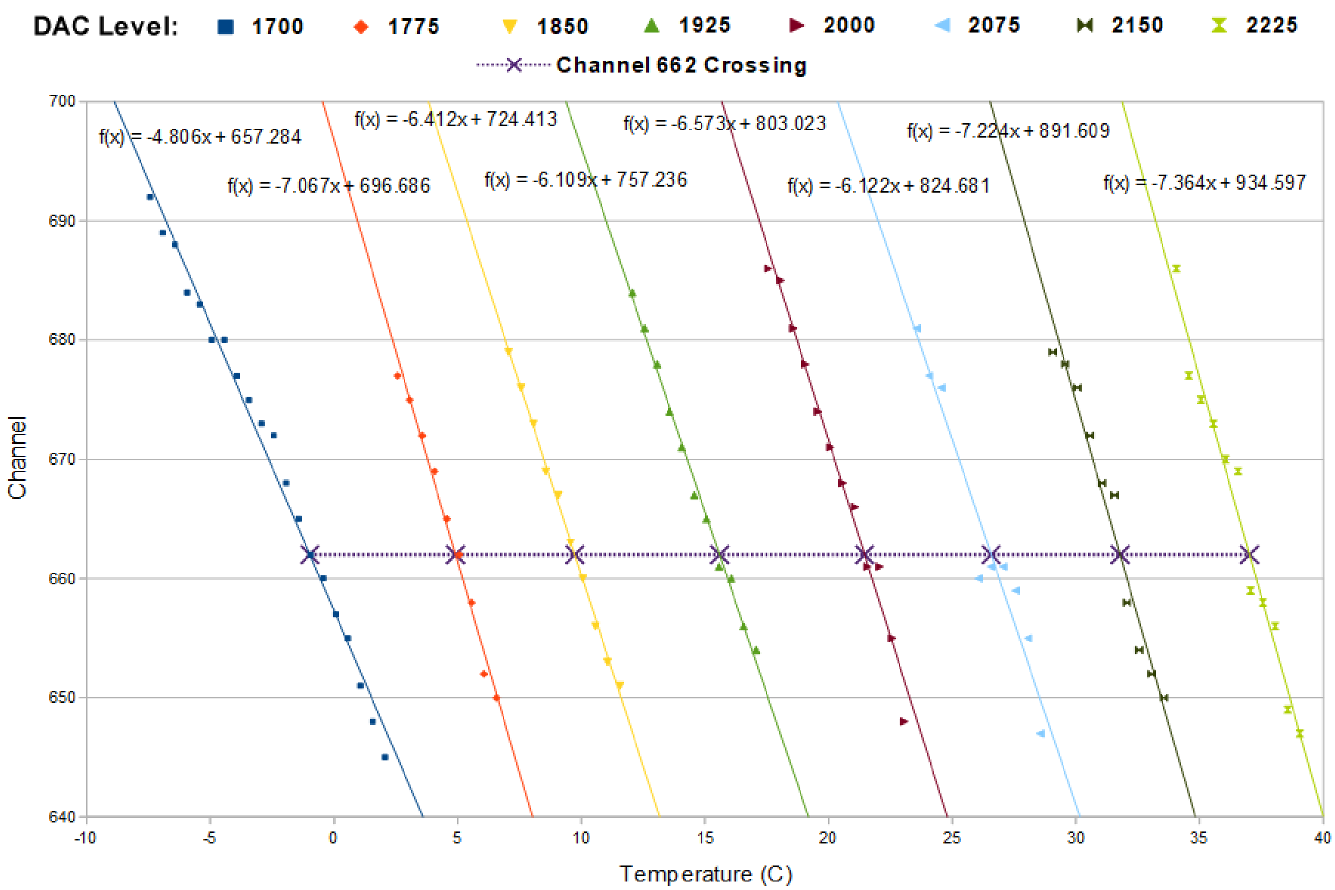


Figure 36: The spreadsheet data separated into the channel location tracks for each DAC level.

The spreadsheet data may now be separated into the channel location tracks for each DAC level, as shown in Figure 36. Line fits to these tracks allow the temperatures of channel 662 crossings to be accurately inferred, as depicted by the X marks in the figure. Plotting DAC levels versus temperatures (Figure 37) provides a set of potential table entries for the TS calibration. A single line fits the middle of the temperature range (5°C to 32°C) pretty well for this example, so a single line segment between the second and seventh points was deemed to be sufficient. However, significant deviations from linearity can occur, especially above and below the room temperature range. The final table entries chosen for this detector are the first two and the last two data points (Figure 38).

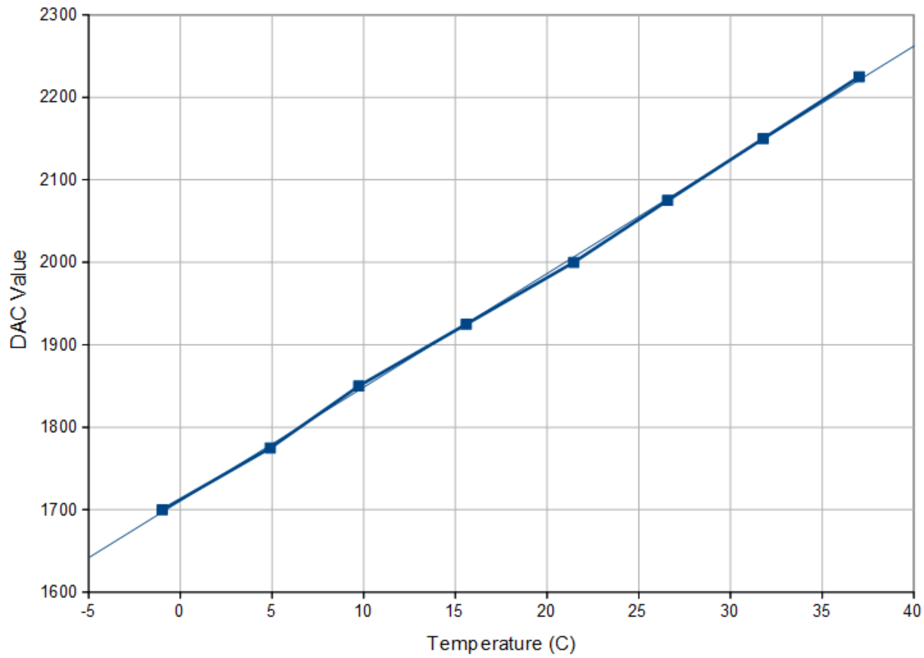


Figure 37: Plot of the 662 crossing from spreadsheet analysis of the previous figure. In this temperature range, the data is well-fit by a straight line.

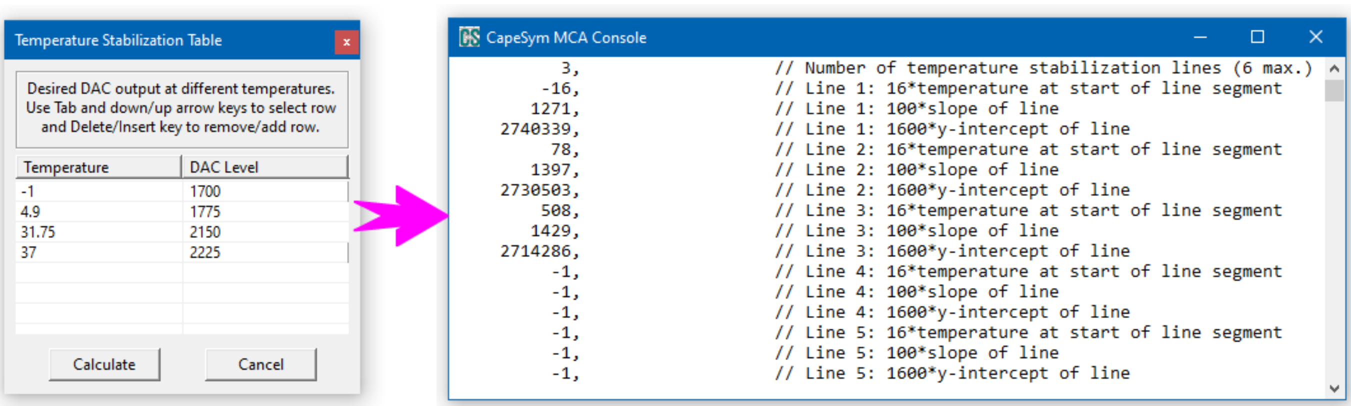


Figure 38: The TS calibration is completed by entering selected points into the table (left), and pressing the Calculate button. The actual lines of the TS calibration are then calculated and added to the MCA parameters which can be viewed in the console. As discussed above, four entries results in the three lines.

The Temperature Stabilization Table allows the user to enter up to seven points to define six lines, describing a piece-wise linear relationship between the DAC and temperature. Fewer lines may be defined using fewer points, but a minimum of two points is required for a line to be calculated. Extrapolation to temperatures lower than the first table entry uses the slope defined by the first two points, and extrapolation to temperatures higher than the last entry uses the last two points. Only the first temperature for each line segment is stored as a parameter, so the last table entry will be forgotten when the lines are calculated. Reopening the table will show one fewer points and temperatures rounded to the nearest 1/16th of a degree. The last point, although forgotten, could be inferred from the temperature calibration lines plot, and restored if desired.

TS Calibration Entry Procedure

1. Device > Connect
2. Device > Stop MCA
3. Device > Calibrations > Temperature stabilization > Edit HV DAC table...
4. Enter the (temperature,DAC) points as discussed in the above text.
5. Press [Calculate] button in the Temperature Stabilization Table dialog
6. Device > Stop mode commands > Update MCA parameters...
7. Press [Send to MCA] button
8. Device > Stop mode commands > Memorize MCA parameters
9. Device > Stop mode commands > Soft Reset

The TS calibration lines can viewed in the console, by using the Parameters to console menu item, or in the MCA parameters dialog. The lines can also be graphed by selecting Device > Calibrations > Temperature stabilization > Plot HV DAC lines... (Figure 39). For this example, only three points are displayed in the plot and in the table, even though four points were originally entered (Figure 38). Recalculating lines from the three points remaining in the table will eliminate one of the four line segments shown in the plot, and result in just two temperature points remaining. Calculating lines from fewer than two entries will be completely eliminate the temperature stabilization parameters.

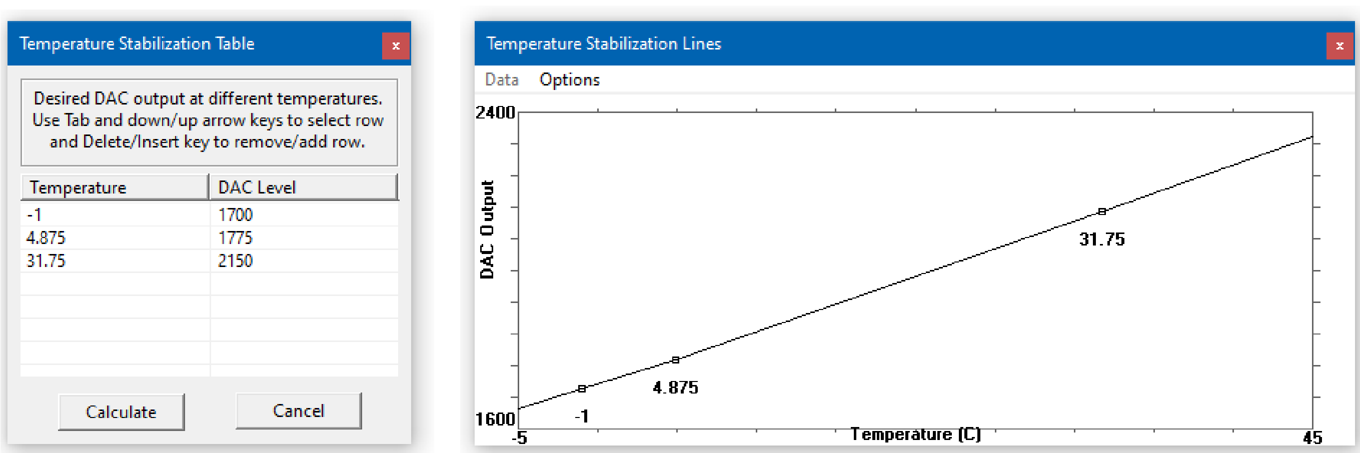


Figure 39: The TS calibration table and lines after the user's entries were processed. Each line segment is represent by a starting temperature point followed by a slope and y-intercept to define the DAC levels.

Once entered in the table, the TS calibration lines reside only in the host software memory. The updated MCA parameters must be sent to the MCA by using the MCA Parameters dialog after entry. The table entries must be entered AFTER connecting to the MCA because the Connect operation overwrites the host's copy of the MCA parameters. For best results use the following procedure.

TS Auto Calibration

The above calibration steps are consolidated in an automatic process which may be invoked by the menu item *Calibrations > Temperature stabilization > Auto calibration...*. This item will open the Auto TS Calibration dialog (Figure 40). The dialog will remain open for the duration of the calibration, which may take more than an hour to complete. Access to other software functions are blocked while the dialog is open, so the software and MCA parameters should be properly configured prior to opening the dialog.

MCA parameters should be configured as in the ***TS Calibration Setup Procedure*** described above, with pulse pileup rejection, temperature stabilization, energy correction, and moving spectrum turned off, and with DAC and temperature feedback enabled. Peak tracking will be used in the host software, so the menu items *Peak type > Mean* and *Label peak when add* should be checked in the Spectrum menu. Place the chilled detector near a Cs-137 test source (500-1500 CPS). Then plug in the USB connector and execute the following procedure. Choose the number of lines assuming each will span no more than 5°C. A 25°C span would need at least 5 lines, but maybe up to 7 lines. The calibration may be completed early with fewer lines by using the Done button when the dialog makes it available.

TS Auto Calibration Procedure

1. Device > Connect
2. Click on the 662 keV photopeak with the left mouse button and add the label 662
3. Device > Calibrations > Temperature stabilization > Auto calibration...
4. Verify that the DAC value is displayed in the Current DAC value box. If not correct, cancel the dialog and set the Feedback type to DAC and temperature, then reopen the dialog.
5. Set the temperature resolution to 0.5°C
6. Set the number of lines to fit. (Seven can be kept, but more fitted before down selection.)
7. Press the [Start] button to start the data collection process

The calibration will proceed in three stages. In stage 1, the DAC will be adjusted to bring the channel location of the photopeak to just above the target channel. As the detector warms up, the shift in the SiPM breakdown voltage will move the photopeak below the target channel. Capturing this movement of the peak through the target channel is the purpose of stage 2. Stage 2 is repeated at a different DAC value for each line specified in Step 6 above. The software records the temperature and peak location for every 0.5°C rise in temperature. These values are reported to the console while the auto calibration is working. Copying and plotting these values would produce a figure similar to Figure 36, but the line fit is done automatically in stage 3 now.

When the channel location falls ~2.3% below the target channel, the DAC is incremented by 75. This is stage 3, which marks the end of data collection for one line and the start of data collection on the next one. Because of the increase in the DAC, the peak location will jump about 20 channels above the target. The calibration then returns to stage 2, with more temperature and peak location points recorded while the detector continues to warm up. Alternations of stage 2 and 3 will continue to be reported in the dialog until all of the data points have been collected for the last line (Figure 41). The dialog must remain open continuously throughout this entire process.

When the final line is complete, the calibration dialog will close and the Temperature Stabilization Table and Lines will be displayed. The table may then be edited and used to calculate the MCA parameters as in the above TS Calibration Entry Procedure. The calibration procedure may be terminated early, provided enough 662 channel crossings were collected to move forward with a calibration. If there is not enough data yet, the Cancel button will simply terminate the process and close the dialog. At which point the entire automatic calibration procedure must be restarted with the detector in a cold state.

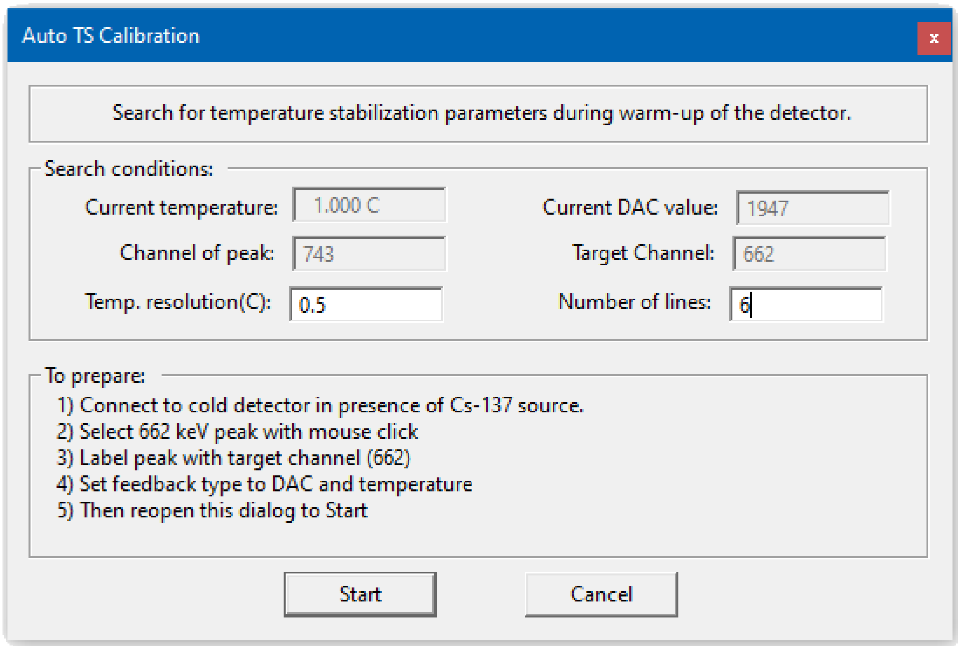


Figure 40: The appearance of the dialog for automatic TS calibration when everything is ready to Start the calibration process.

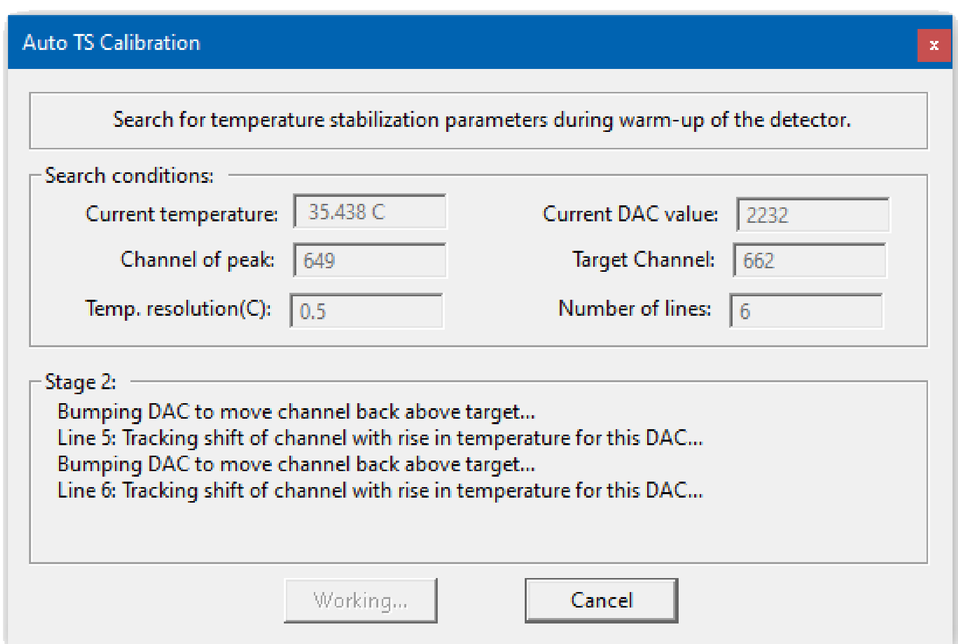


Figure 41: The appearance of the dialog for automatic TS calibration near the end of the data collection process.

Quick Two-Point TS Calibration

If temperature stabilization is only needed at room temperature, a quick two-point stabilization will suffice. The quickness of the two-point calibration comes from the fact that the ***Divisor Adjustment Procedure*** (Step 3) can be done at the same time as stabilization, or it can be skipped altogether by using an initial DAC adjustment to place the target photopeak at the desired channel for the first temperature point.

The idea for this procedure is to record the DAC for when the detector is actually at room temperature, and then record it again after the MCA has heated up the detector by several degrees. These two temperature states can usually be controlled by a fan blowing room temperature air across the MCA. When the fan is on, the MCA should remain near room temperature, and when the fan is off the MCA should heat up the detector by several degrees. Aim for a temperature difference of more than 5ºC for the two points. In self-heating is insufficient for a large temperature difference, try blocking convective air flow around the device or placing it against a warm surface such as a cup of coffee or a cup warmer.

MCA parameters can be configured as in the ***TS Calibration Setup Procedure*** described above, with pulse pileup rejection, temperature stabilization, and energy correction turned off, and with DAC and temperature feedback enabled. However, it is not necessary to disable tracking mode. Tracking mode might be helpful during this procedure, as long as the Moving spectra provide enough counts to accurately determine the photopeak channel location while the temperature of the detector is slowly drifting.

Quick Two-Point Calibration Procedure

1. With the fan on, turn on the MCA and Connect to it. Note the first DAC and temperature point.
2. Note the channel location *c* of the 662 keV photopeak
3. Use *Device* > *Stop MCA* to enter Stop mode
4. Device > Stop mode commands > Update MCA parameters...
5. Modify the divisor parameter according to the formula: $\text{new divisor} = \text{old divisor} \times (\frac{c}{662})$
6. Press [Send to MCA] button
7. Device > Stop mode commands > Memorize MCA parameters
8. Device > Stop mode commands > Soft Reset
9. Re-Connect to the MCA and check the channel location of the 662 keV photopeak. The photopeak should be close to channel 662 while the temperature is still near room temperature.
10. Turn the fan off and let heating by the MCA warm up the detector several degrees
11. Adjust the DAC to shift the photopeak location back to near channel 662
12. Note the second DAC and temperature point
13. Device > Stop MCA
14. Device > Calibrations > Temperature stabilization > Edit HV DAC table...
15. Enter the two (temperature,DAC) points noted in steps 1 and 12
16. Press [Calculate] button in the Temperature Stabilization Table dialog
17. Device > Stop mode commands > Update MCA parameters...
18. Verify that the temperature stabilization parameters were updated by the [Calculate] button
19. Set the temperature stabilization on/off parameter to 1
20. Press [Send to MCA] button
21. Device > Stop mode commands > Memorize MCA parameters
22. Device > Stop mode commands > Soft Reset
23. Turn the fan back on, then re-Connect and verify that the 662 keV photopeak location is stabilized near channel 662 as the detector module cools off.

TS Calibration by DAC Servo

The latest firmware (see Table 0) contains an operating mode in which the photopeak is continuously servoed to the desired channel location by adjusting the DAC output. Once the photopeak reaches the target channel, the DAC value for the current temperature is recorded into non-volatile memory for later fitting of the temperature stabilization calibration lines. The fitting procedure is invoked by the *Calibrations > Temperature stabilization > Fit peak servo data* menu item in Run mode. The menu item will be grayed out in Stop mode. If the menu item is grayed out in Run mode, then the MCA hardware does not support the DAC servo operation, as noted above in the section on the **Peak Target for DAC Servo** parameter.

The peak target parameter specifies the desired channel location of the only photopeak in the energy spectrum within 12% of the target channel. When a positive target channel and photopeak are present, the MCA will automatically adjust the DAC to move the peak to the target. The servo makes one DAC adjustment every time the full depth of the moving spectrum has been updated. So if the depth is 20 and the communication interval 1s, then the DAC is adjusted every 20 seconds. The size of the adjustment is proportional to the error between peak and target. If the peak is already at the target when calculating the adjustment, then the DAC value will be recorded in FRAM for the current temperature. Once enough data has been recorded, the aforementioned *Fit peak servo data* command may be used to obtain a piece-wise linear fit that will provide the temperature stabilization parameters.

To prepare for the DAC servo, it may be desirable to erase any prior recorded data that is already stored in FRAM. This can be done by using the Update MCA Parameters dialog to set the peak target parameter to -1. On startup, the MCA detects the -1 value and sets servo data to zero. This can be verified by using the *Fit peak servo data* to retrieve the servo data, and then *Console > DAC vs temp to console* to display it.

DAC Servo Calibration Procedure

1. Place weak Cs-137 source near detector to increase count rate to at least 20x background
2. The channel location of 662 keV photopeak should be within 12% of 662 to start the servo
3. Use *Device > Stop MCA* to enter Stop mode
4. Modify parameters using *Device > Stop mode commands > Update MCA parameters...*
    i. Temperature stabilization = 0
    ii. Spectrum type = 0
    iii. Moving spectrum = 1
    iv. Depth of moving spectrum = 16
    v. Communication interval = 10
    vi. Peak target for DAC servo = 662
5. Use the *Send to MCA* button, then *Memorize MCA parameters*
6. Use *Device > Run mode configuration > Spectrum data type > Channel zero is > DAC and temperature* to allow observation of the DAC servo adjustments
7. Verify that the DAC is updated (once per 16 seconds) to reduce the error

Now the MCA may be disconnected from the host, powered off, and reconnected to battery power. The DAC servo will resume on every power up as long as the peak target parameter remains at 662 and the Cs-137 photopeak is within 12% of this target on startup. However, remember that the startup DAC value will be given by the separate DAC parameter, so powering up the detector at an extreme temperature might result in the photopeak being out-of-range of the DAC servo. The recommended procedure is to keep the MCA powered on continuously while running the DAC servo, which can be accomplished using a battery pack that is moved in and out of the environmental chamber with the MCA.

To stop the DAC servo, simply set the peak target parameter to zero.

DAC Servo Data Fitting Procedure

1. Re-connect the MCA to the host computer
2. While still in Run mode, use *Calibrations > Temperature stabilization > Fit peak servo data* to retrieve and fit lines to the DAC servo data (Figure 42)
3. To see the raw data use *Console > DAC vs temp to console* to print to the console
4. Open the Update MCA Parameters dialog and verify that the temperature stabilization parameters were updated (they should agree with fitted line segments shown in the console)
5. Turn the DAC servo off by setting peak target parameter to zero
6. Use the *Send to MCA* button to transfer the new parameters

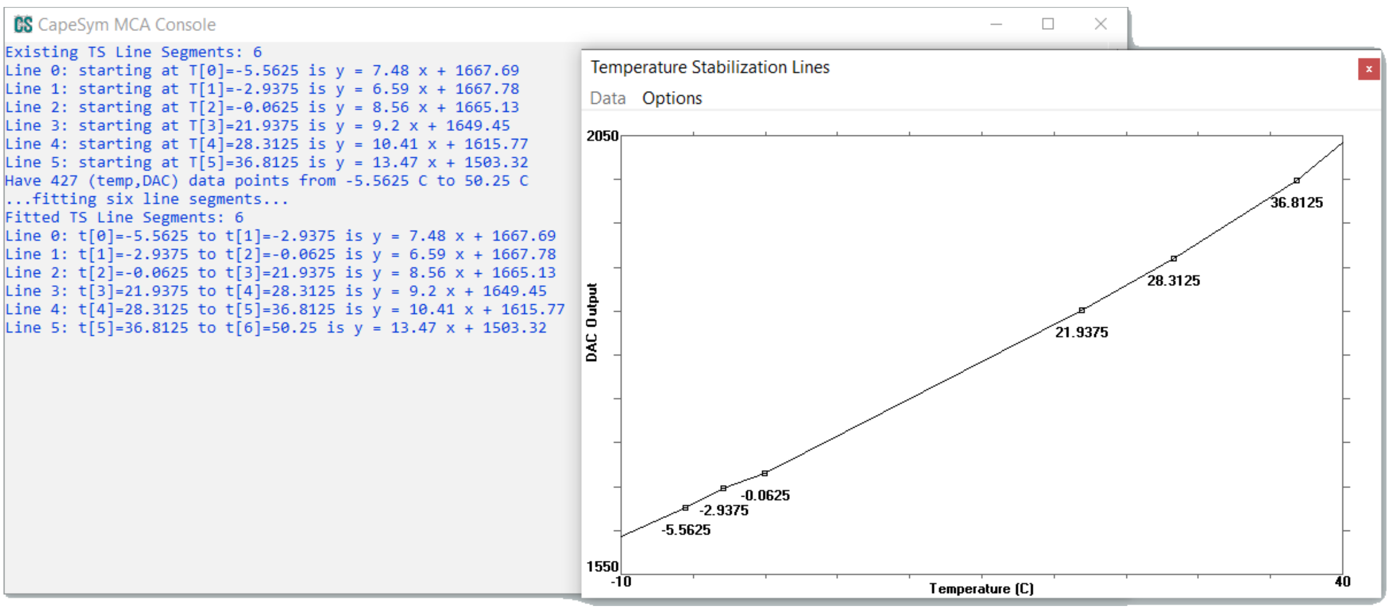


Figure 42: The results of a successful piece-wise linear fit to the servo data, as reported in the console of the CapeMCA host software and its lines plot. The fitting algorithm finds the optimal set of six line segments to cover the entire range of non-zero servo data with the minimum fitting error. The algorithm then updates the TS parameters based on this fit. These new parameters must be sent to the MCA and then memorized to permanently overwrite the old TS parameters.

Step 6: Energy Correction

The detector response is not proportional to the energy deposited over the full gamma energy range, from 10 keV to 4000 keV. This non-proportionality means that stabilization of 662 keV at channel 662 will not also place other characteristic gamma energies at their expected channel locations. For example, the Co-60 photopeak at 1174 keV will be stabilized at a much lower channel than 1174 when the Cs-137 photopeak is used for TS calibration.

<< Calibration of temperature stabilization must be done first >>

The MCA firmware allows the channel locations of a wide range of gamma energies to be remapped to appropriate channels, through entries in the Energy Correction Table (Figure 43). The procedure for updating the Energy Correction Table is given in this section.

The channel entries for the Energy Correction Table must be measured on one or more spectra after temperature stabilization has been calibrated and while temperature stabilization is turned on. For best results, the temperature stabilization will have also been validated, as described in the next section.

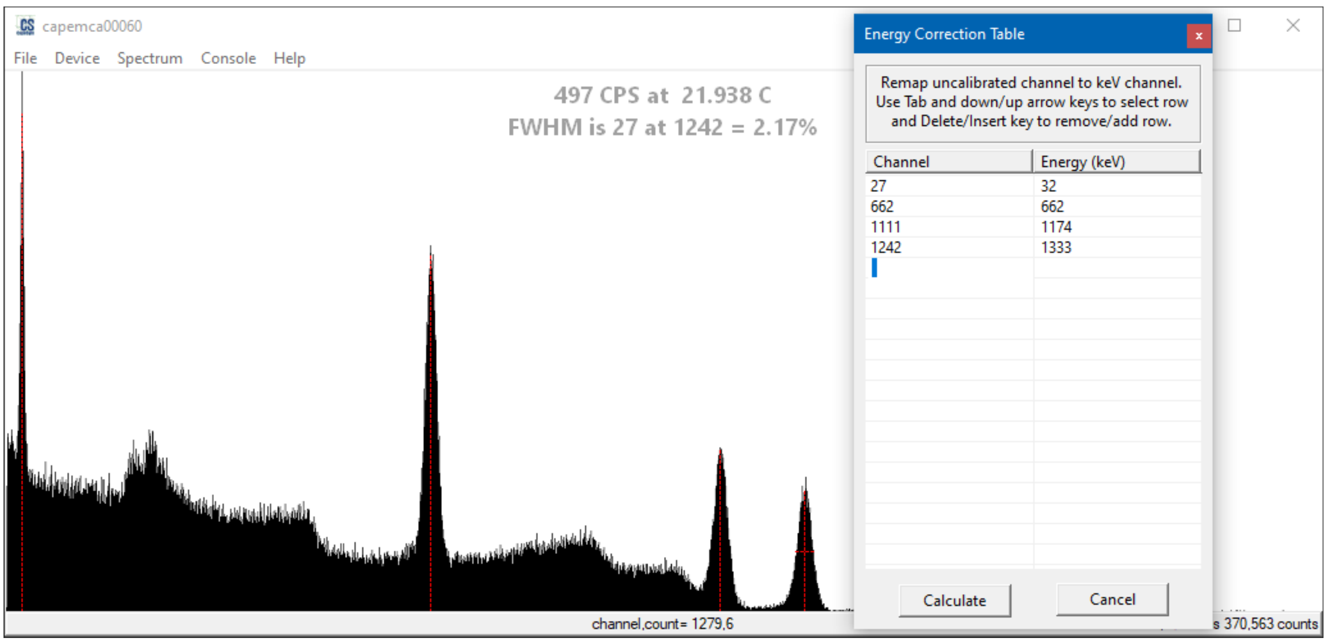


Figure 43: The Energy Correction Table specifies that peaks found at particular channels (first column) are to be remapped to the channel locations corresponding to their characteristic gamma energies in keV (second column).

To demonstrate the procedure, a spectrum from Cs-137 and Co-60 is used, which has four peaks at energies of about 32 keV, 662 keV, 1174 keV, and 1333 keV (Figure 44). Only four peaks are used for calibration here, but many more peaks would be needed to accurately compensate for detector non-proportionality over the full energy range. The most non-linear region of non-proportionality is below 662 keV. The single peak at 32 keV is not sufficient to get good accuracy throughout the low-energy range. Additional calibration peaks will be needed in this range to guarantee an accurate calibration.

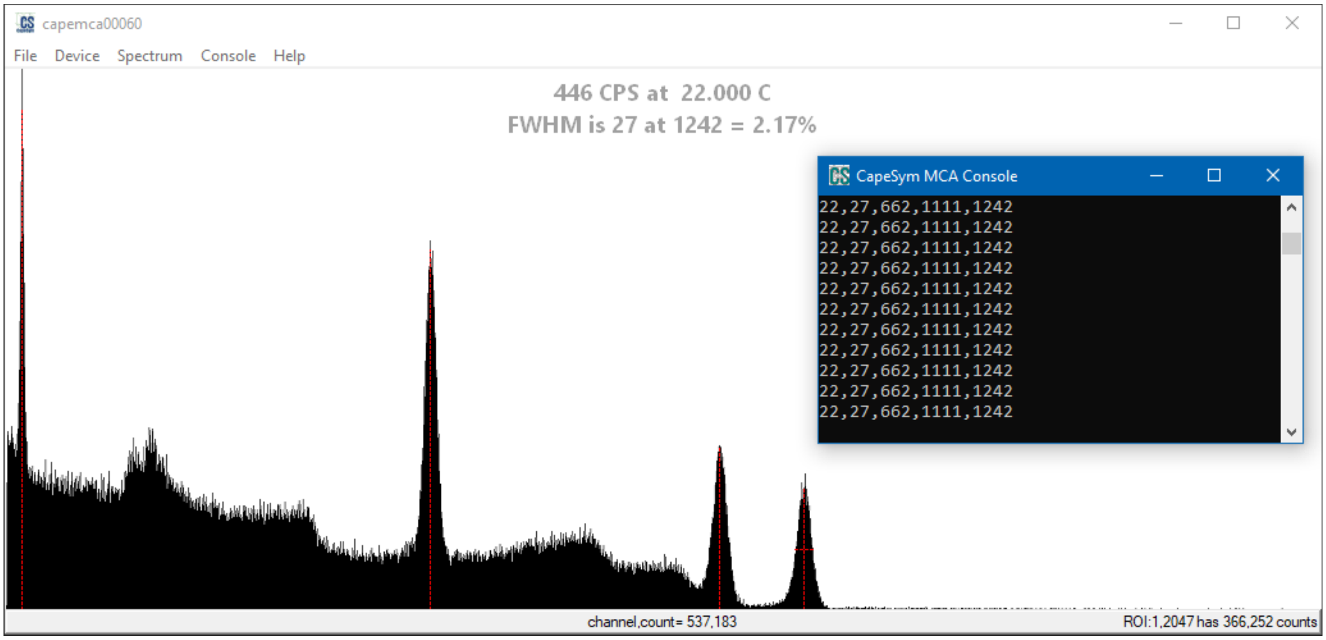


Figure 44: The process of measuring the channel locations of the four peaks of the spectrum from a combination of Co-60 and Cs-137 . Peaks are marked and tracked while being continuously reported the console, until sufficient counts have be obtained to ensure accurate channel locations.

EC Calibration Procedure

1. Device > Connect
2. Make sure temperature stabilization is ***enabled***, while both energy correction and pulse pile rejection are ***disabled***
3. Device > Run mode configuration > Zero out spectrum
4. Use left mouse button clicks to select the peaks to track
5. Spectrum > Peak type = Mean
6. Spectrum > Peaks to console
7. Console > Show console
8. Wait for spectrum to accumulate a large number of counts for accuracy
9. Device > Stop MCA
10. Device > Calibrations > Energy correction....
11. Enter channel locations as listed in console and enter their gamma energies
12. Press [OK] to calculate the MCA parameters
13. Device > Stop mode commands > Update MCA parameters...
14. Press [Send to MCA] button to transfer the parameters
15. Device > Start up
16. Device > Run mode configuration > Energy correction > Enable EC
17. Device > Run mode configuration > Zero out spectrum
18. Use right mouse button to erase the old peak tracks
19. Use left mouse button clicks to select the peaks to track
20. Console > Show console
21. Wait for spectrum to accumulate a large number of counts to verify the correction
22. Device > Stop MCA
23. Device > Stop mode commands > Memorize MCA parameters

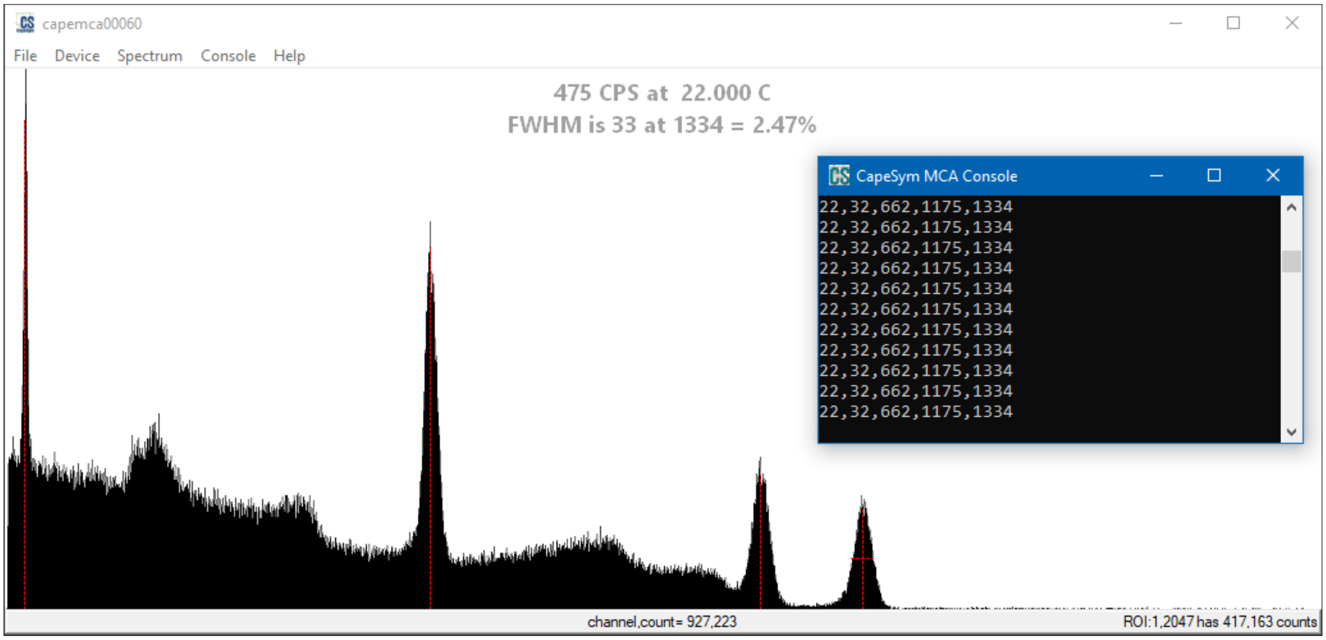


Figure 45: Validation of energy correction is Step 21 of the calibration procedure. The new peak locations reported to the console closely match the specified energies.

As shown in Figure 45, the corrected peaks are within one channel of the desired locations, for an accuracy of less than 1%.

Stabilization and Energy Validation

After the temperature stabilization lines have been memorized, the sensor should be tested over a wide temperature range to verify the validity of the calibration. Further adjustments of the DAC at temperatures with significant deviations from the stable channel may then be made in the HV DAC table to update the calibration. Once the temperature stabilization (TS) is satisfactory, energy correction (EC) can also be applied and the combined effects of both adjustments validated over the desired temperature range.

In the following, two procedures are described for the validation. The **Quick Stability Check** makes use of the moving spectra capability to allow the channel location of a peak to be easily tracked during warming of the detector. However, there is no permanent record of the stabilization with this method. The second validation method involves Auto Saving a spectrum after every 0.5°C rise in temperature while the detector is warming. Then Auto Load with photopeak labeling may be used to track multiple peaks and create a spreadsheet of the stability performance, as demonstrated below.

For both test scenarios, the temperature of the detector and MCA will need to be varied over a wide range. An environmental temperature chamber may be helpful, but a household refrigerator might suffice. Putting the sensor in the freezer for a hour will lower the temperature well below zero. Letting it warm to room temperature would then provide a temperature range of at least -5°C to 25°C. Transferring the sensor to a warming plate after it reaches room temperature can extend the range further, but try to limit the range to about 40°C. Above 40°C noise is likely to become a problem due to increased dark current in the SiPMs.

Quick Stability Check

1. Device > Connect
2. Device > Stop MCA
3. Device > Stop mode commands > Update MCA parameters...
   i. Temperature stabilization = 1
   ii. Energy correction = 1
   iii. Turn on Moving spectrum = 1 and Depth of moving spectra = 32
   iv. Communication interval = 10 (for 1 second updates)
4. Press [Send to MCA] button
5. Device > Start up
6. Click on 662 keV peak in the main window and set Spectrum > Peak type > Mean
7. Continuously monitor the peak location as the sensor warms up

Create Stability Record

1. File > Auto save...
   1. Filename: spectrum_0000.csv
   2. Check *Encode 16-temperature with 16-bit CPS*
   3. Save file at intervals of Temp. change = 0.5
   4. Leave ENABLE AUTO SAVE unchecked for now
2. Press [OK] to keep these Auto save settings
3. Spectrum > Peak type > Mean
4. Remove the sensor from freezer and place near the Cs-137 source for 500-1500 CPS
5. Plug in the USB cable.
6. Device > Connect
7. Device > Run mode configuration > Temperature stabilization > Enable TS
8. File > Auto save... to check the ENABLE AUTO SAVE and hit OK
9. Wait for detector to warm up all the way while auto-saving spectra.
10. File > Quit autosave
11. Device > Disconnect
12. File > Load spectrum to load the first spectrum in the data set: spectrum_0001.csv
13. Left mouse click on the photopeak(s) to track.
14. Spectrum > Peaks to console
15. Console > Show console
16. File > Auto load...
    1. Filename: spectrum_0001.csv
    2. Time (seconds) = 1
    3. Loop: check *Never*
    4. Check ENABLE AUTO LOAD
17. Press [OK] to begin the Auto load operation.
18. Observe that temperature and channel location is being tracked correctly and reported to the console. The sequence will stop automatically when the all files have be processed.
19. Uncheck Spectrum > Peaks to console
20. In the console, use the mouse pointer to highlight the temperature and peak location data, then press Enter to copy this data to the clipboard.
21. Open a spreadsheet and paste the data into it.

To validate the stabilization, the above procedure was used on a sensor twice, once with TS disabled and once with TS and EC enabled (Figure 46). The detector was removed from the freezer and exposed to Cs-137 and Co-60 sources. A spectrum was recorded after every 0.5ºC change in temperature using Auto Save. The peaks were then labeled and printed to the console during Auto Load. The console data was copied and pasted into a spreadsheet for plotting. With TS enabled, the peak locations were constant over a wide range of temperatures, demonstrating the accuracy of the TS calibration.

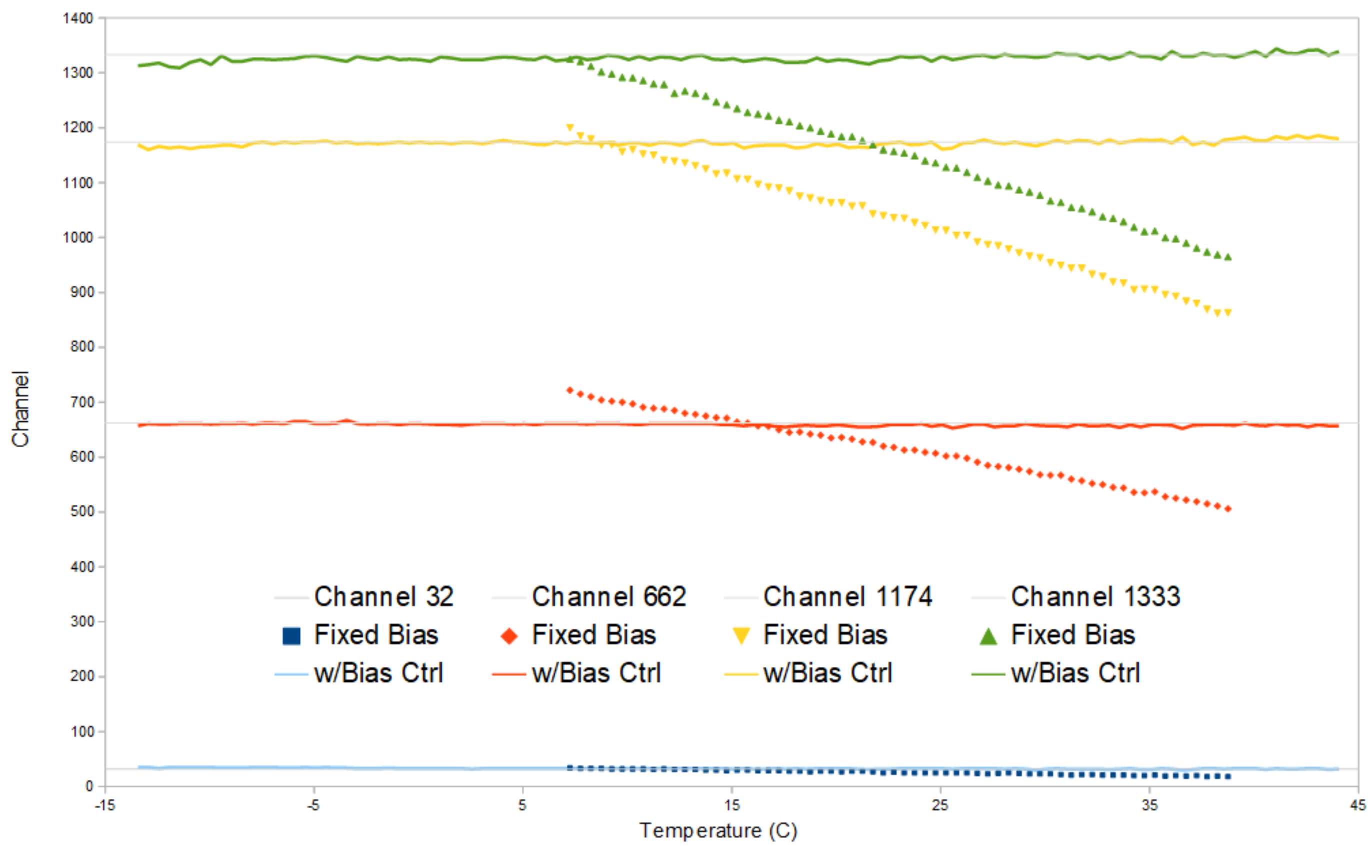


Figure 46: The gamma energy peaks of Cs-137 and Co-60 closely track the desired channels over a wide range of temperatures after calibration of the temperature stabilization and energy correction. Prior to these calibrations, when bias voltage was constant, a change in temperature caused a shift in the channel location of characteristic peaks that was proportional to the gamma energy.

Step 7: Pulse Pileup Rejection

Pulse pileup may detected by comparing the width of pulses at high counts rates to the expected widths at low count rates. Figure 47 shows the pulse width spectrum at a count rate of ~2000 CPS. Compare this to Figure 48 obtained at 100 times lower count rate. There are many pulse widths above the expected pulse width curve because they are from two overlapping pulses.

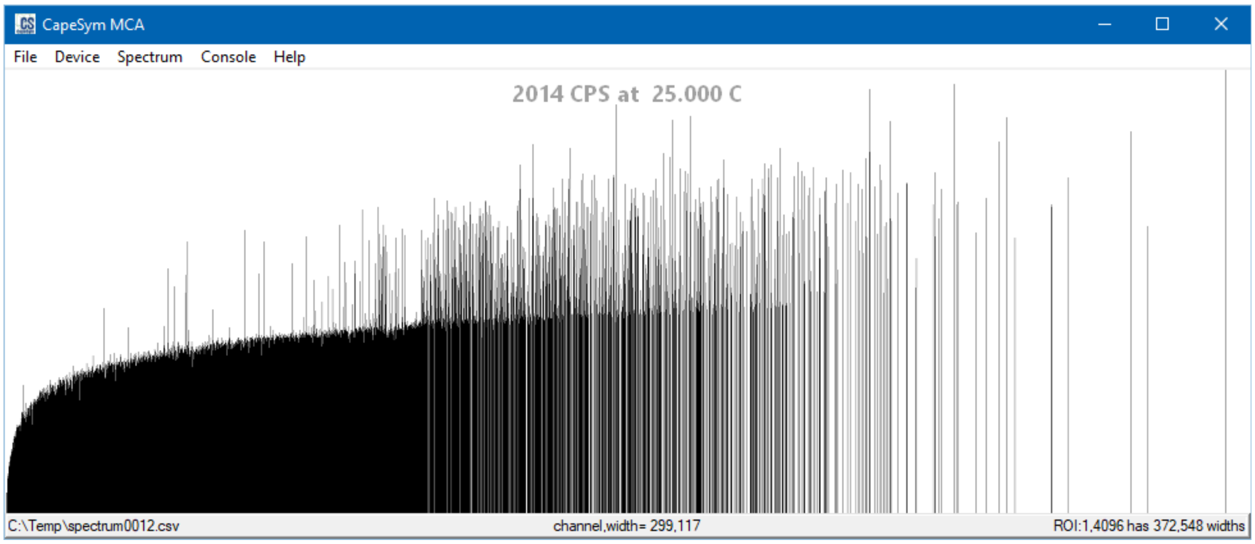


Figure 47: The pulse width spectrum at ~2000 CPS.

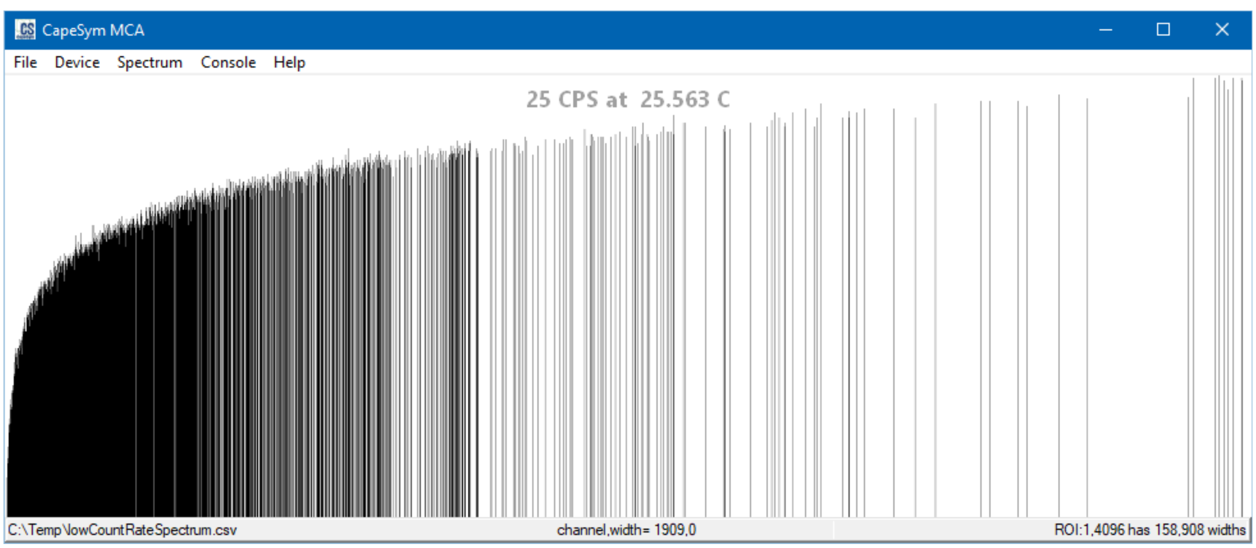


Figure 48: The pulse width spectrum at ~20 CPS.

Pulses having widths far from the expected curve may be easily rejected once the pulse width curve is described mathematically. To obtain this description, first acquire a pulse width spectrum in a low rate environment, for example in normal background. Ideally, the pulse width spectrum used for calibration would include all the energy channels. As a general rule, the denser the pulse width data, the better the curve fit. It is especially important to acquire plenty of high-energy pulses in the upper channels. If there is an existing calibration, you may want to turn on the Pulse Pileup Rejection (PPR) during the low count rate acquisition to further ensure the ideal case of no pileups being recorded.

The pulse width curve from the current calibration may be overlaid on the acquired spectrum by using the Calibrations menu to select *Pulse pileup rejection > Plot pulse width limits*, as shown in Figure 49. Recall that the current calibration parameters from the MCA hardware were transferred to the host software when the USB connection was made. The overlaid plot allows evaluation of the goodness of fit of these the current calibration parameters. Only pulses with widths between the blue and magenta lines are added to the spectrum when pulse pileup rejection is turned on.

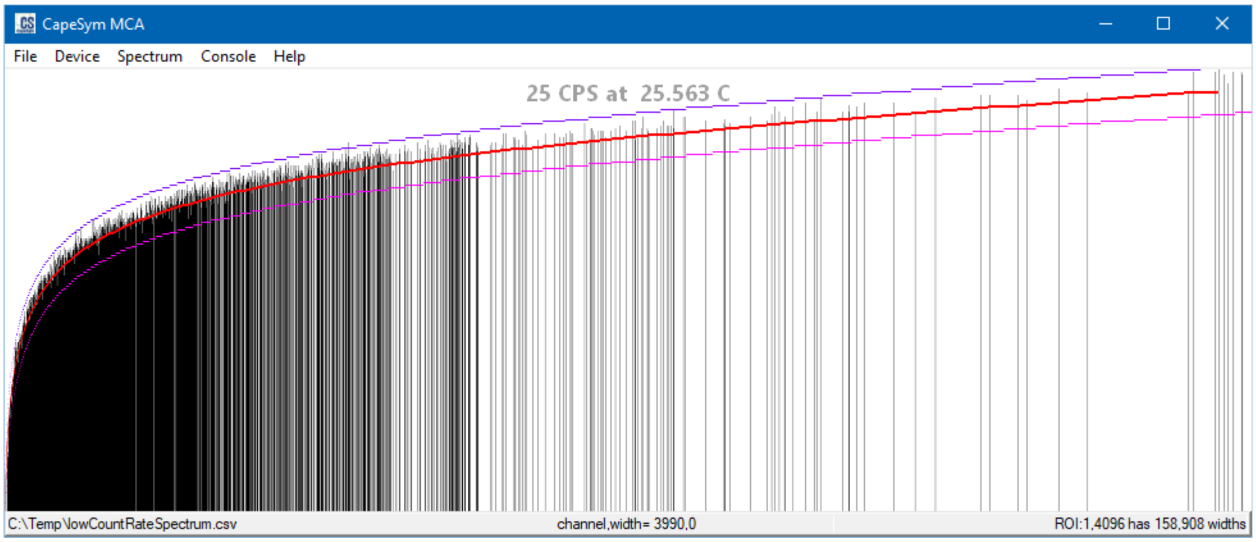


Figure 49: The plot width curve and limits from an existing calibration are overlaid on the pulse width spectrum.

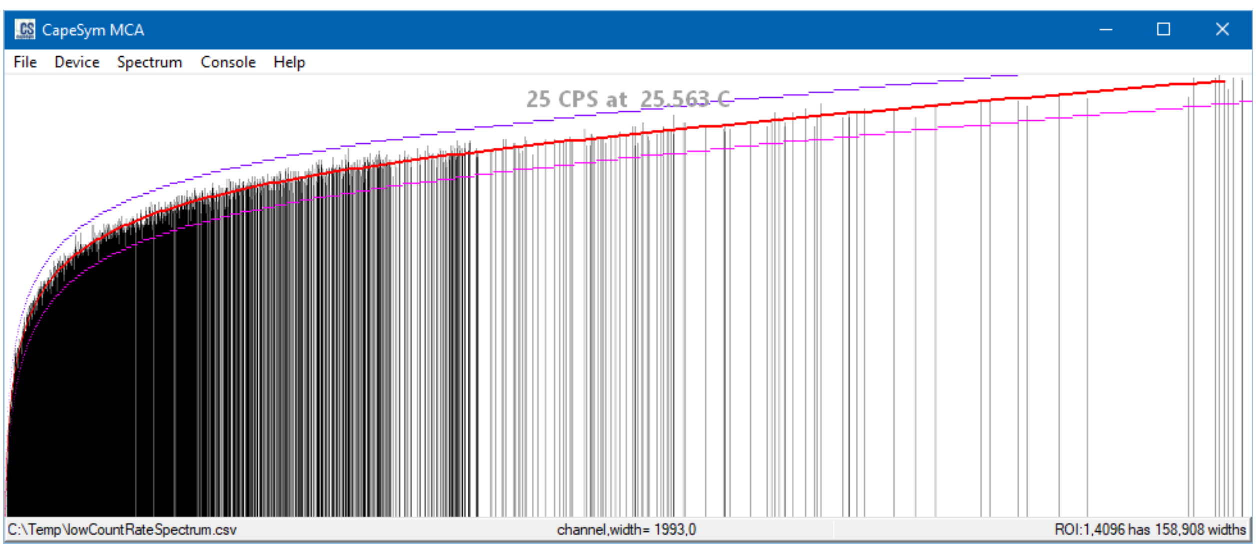


Figure 50: The pulse width curve fit to the pulse width spectrum is closer to the data.

The coefficients of the fitted curve (red line) may be recalculated in the host software by selecting *Pulse pileup rejection > Recalculate from spectrum*. The overlaid plot will be updated immediately, helping to visualize the change produced by recalculation, as depicted in the Figure 50. Be sure to check the new curve fit in the lower channels by zooming in on them with the mouse wheel (Figure 51). Old and new curve fit coefficients are written to the console during recalculation.

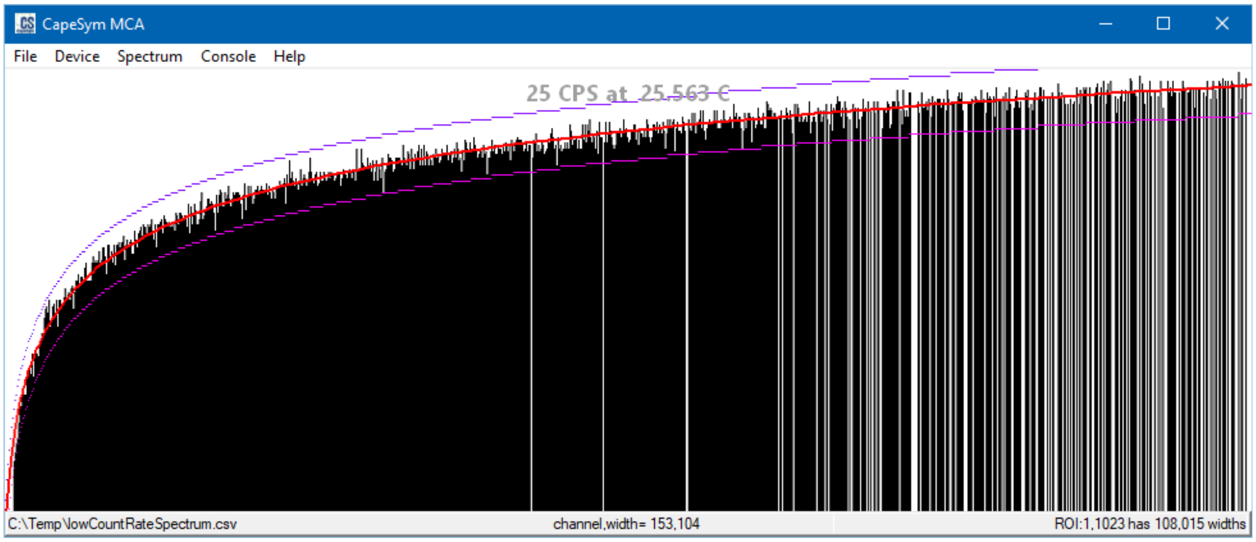


Figure 51: Zooming in on the lower energies to examine the pulse width curve fit closely.

If the change produced by recalculating the coefficients is not an obvious improvement, the pulse width limits calibration should probably be abandoned. At this point, the coefficients from the old calibration have been overwritten in the host software by the Recalculate command, but they can be recovered by exiting Stop mode, and then using a Disconnect/Connect sequence to reload them from MCA hardware.

PPR Calibration Procedure

1. Connect to the MCA and record a pulse width spectrum at low count rate
2. Stop the MCA but leave it connected
3. Check existing calibration (Calibrations > *Pulse pileup rejection* > *Plot pulse width limits*)

Only modify the existing calibration if a significant improvement is obtained in the next step

4. Recalculate curve fit (Calibrations > *Pulse pileup rejection* > *Recalculate from spectrum*)
5. Adjust offsets, if necessary (Calibrations > *Pulse pileup rejection* > *Enter limit offsets...*)
6. Send new parameters to MCA (Stop mode commands > *Update MCA parameters...)*
7. Restart the MCA without disconnecting it and test PPR
8. Switch Spectrum data type back to *Pulse count* and then *Memorize MCA parameters*

To refine the calibration, the offsets from the fitted curve (red) to the upper (blue) and lower (magenta) pulse width limits may now be adjusted. These limits set the range of acceptable pulse width variations along the whole curve fit. The pulse width and these offsets are both expressed in terms of the number of samples at the sampling rate of the MCA. Offsets of 10 samples, about 7% of a large pulse width of 150 samples, appear to give reasonable PPR while not rejecting low energy pulses.

Once the new parameters are established they can be sent to the MCA (RAM memory) for live testing before making them permanent. To do this, select *Send to MCA* from the MCA Parameters dialog. Then Start up the MCA loop to start receiving spectra again. If PPR is enabled, now it will be using the new curve fit and limits, as shown in Figure 52.

The new PPR calibration can be made permanent by selecting *Flash parameters in MCA* from the MCA Settings menu before disconnecting the MCA. Before flashing the parameters, switch the spectrum type back to *Pulse count* so that the MCA will power up with the default spectrum type. Remember that all of the MCA settings are made permanent by the Flash command.

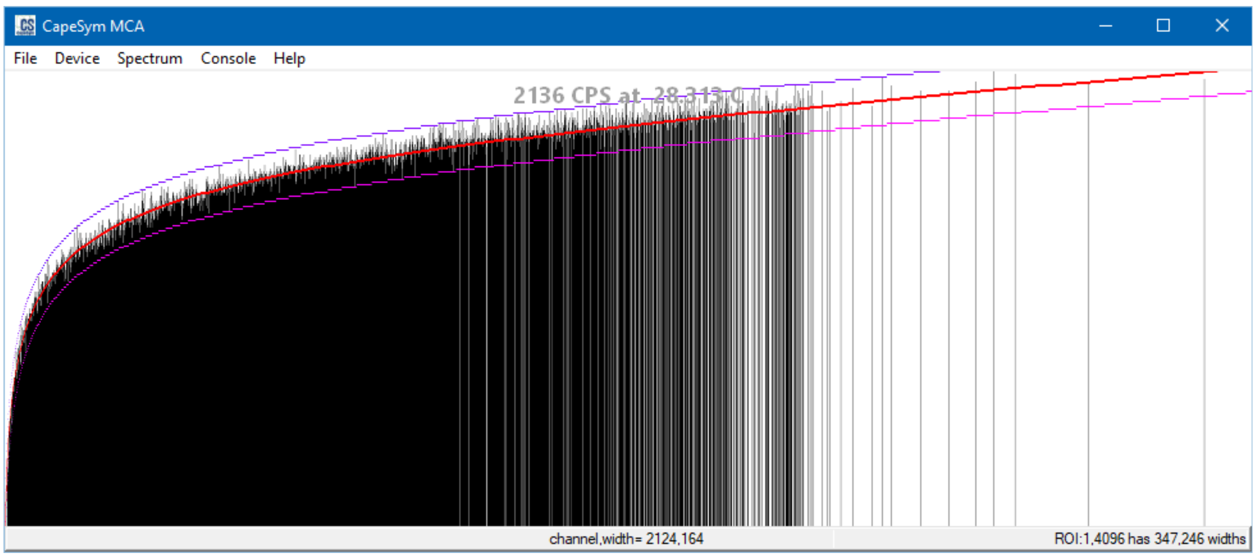


Figure 52: Testing the new pulse width curve and limits at high count rate after sending the parameter changes to the MCA.

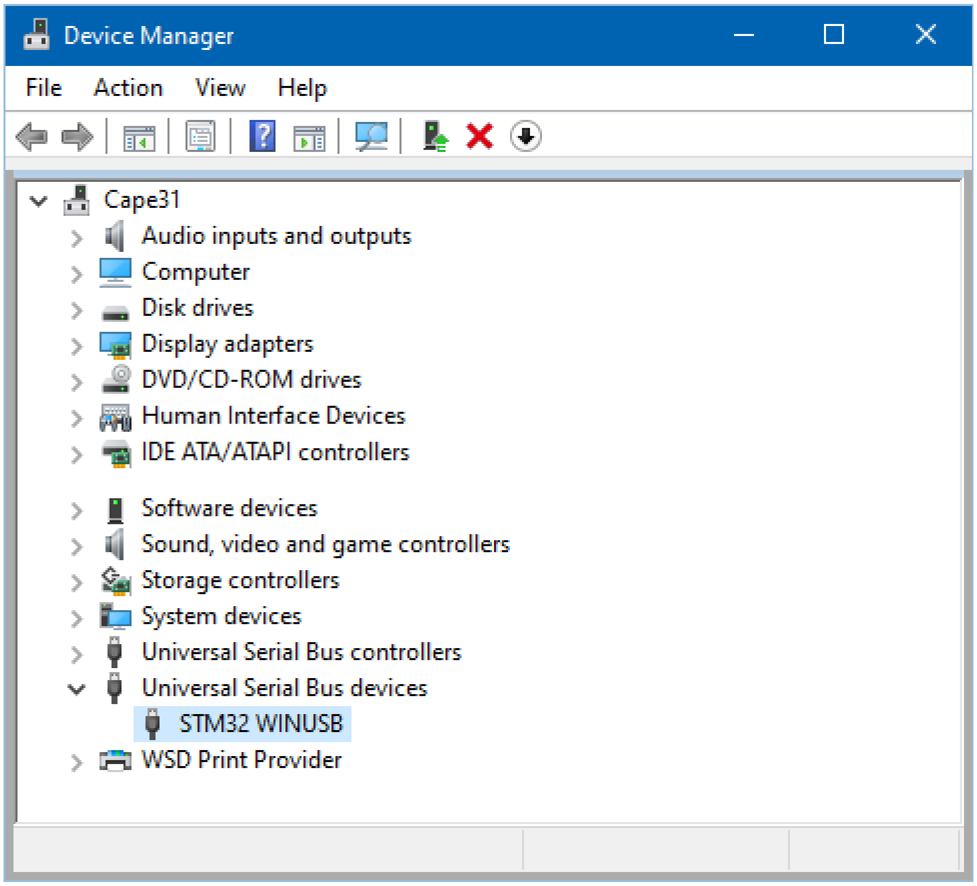
Constant Width Pulses:

As noted above, the adjustable filter parameters (when supported) allow the pulse width to be made constant over a wide range of energies, which will improve the accuracy of counting statistics. The pulse width curve fitting procedure should not be used to define a constant pulse curve. Instead, measure the pulse width by drawing the y-axis lines while displaying the pulse width spectrum. Then directly modify the *Pulse width curve fit coefficient 1* in the MCA Parameters dialog, setting it to 10,000 times the measured pulse width. For example, if the pulse width was measured to be 40, enter 400,000 for the coefficient and set all the other pulse width curve coefficients to zero. When the pulse width curve is plotted, it should appear as a straight, horizontal line at the correct pulse width. The upper pulse width limit can then be set a few samples above the line, while the lower pulse width limit is set to the pulse width, so that all pile ups are rejected but no short pulses in the low-energy channels are rejected.

Don't forget to send the updated pulse limiting parameters to the MCA, and memorize them so that they will be become operational whenever pulse pileup rejection is turned on.

Appendix A: USB Device Interface

The Windows desktop application reads from and writes to the WINUSB device driver using the WinUsb API. The driver should automatically appear in the Device Manager when the CapeSym MCA hardware is plugged into any USB port under Windows 8 or higher. The STM32 WINUSB device interface may be identified with vendor identification number (VID) of 0x4701 in hexadecimal, and product identification number (PID) of 0x0290. To allow multiple MCAs to connect to one computer, each MCA must include a unique serial number string as part of the device descriptors, such as "capemca00032".



For Windows 7 and lower, the MCA will not be automatically identified as a USB device that uses the WinUSB driver. Instead, the WinUSB driver must be associated with the device's VID, PID and DeviceInterfaceGUID of {13EB360B-BC1E-46CB-AC8B-EF3DA47B4062} through a .inf file. A simple .inf file for making this association is listed in the following code box. Copy this code and paste it into a text file (e.g. using Notepad) and then save the file to STM_WINUSB.inf in an easily accessible folder such as C:\Temp. Open the Device Manager from the Control Panel, and find the broken STM WINUSB device. Use a right mouse click on the device to select *Update Driver Software...* and then choose *Browse my computer for drivers*. Use the Browse button to locate the folder containing STM_WINUSB.inf and then click the Next button. If a message appears saying that the driver is not signed, just select *Install this driver software anyway* to continue. The progress bar for *Installing driver software...* should display for a minute or two and then report a successful install. Now the MCA device should be properly recognized for connecting from the Device menu of the CapeMCA program.


```
;
; .inf file for associating WinUsb driver with CapeMCA USB devices
;
[Version]
Signature = "$Windows NT$"
Class     = USBDevice
ClassGUID = {88BAE032-5A81-49f0-BC3D-A4FF138216D6}
Provider  = %ManufacturerName%
CatalogFile = WinUSBInstallation.cat
DriverVer=09/04/2012,13.54.20.543

; ========== Manufacturer/Models sections ===========

[Manufacturer]
%ManufacturerName% = Standard,NTamd64

[Standard.NTamd64]
%DeviceName% =USB_Install, USB\VID_4701&PID_0290

; ========== Class definition (for Windows 8 and ealier versions)===========

[ClassInstall32]
AddReg = ClassInstall_AddReg

[ClassInstall_AddReg]
HKR,,,,%ClassName%
HKR,,NoInstallClass,,1
HKR,,IconPath,%REG_MULTI_SZ%,"%systemroot%\system32\setupapi.dll,-20"
HKR,,LowerLogoVersion,,5.2

; =================== Installation ===================

[USB_Install]
Include = winusb.inf
Needs   = WINUSB.NT

[USB_Install.Services]
Include =winusb.inf
Needs   = WINUSB.NT.Services

[USB_Install.HW]
AddReg=Dev_AddReg

[USB_Install.Wdf]
KmdfService=WINUSB, WinUsb_Install

[WinUsb_Install]
KmdfLibraryVersion=1.11

[Dev_AddReg]
HKR,,DeviceInterfaceGUIDs,0x10000,"{13EB360B-BC1E-46CB-AC8B-EF3DA47B4062}"

[Strings]
ManufacturerName=""
ClassName="Universal Serial Bus devices"
DeviceName="STM32 WINUSB"
REG_MULTI_SZ = 0x00010000
```

In Run mode, the MCA device will respond to only one USB command from the host computer at each communication interval, typically once per second. Every command is two bytes long, and only the first two bytes received are retained for processing. Additional two-byte commands received while the MCA is processing pulses will be discarded. For maximum compatibility, the host computer should send only one command per communication interval.

Table 8: USB Commands in Run Mode

Byte 1	Byte 2	Command	Reply Bytes
0	0	return packet0 data structure	64
0	1	return 256 x 32-bit integer spectrum	1024
0	2	return 512 x 32-bit integer spectrum	2048
0	4	return 1024 x 32-bit integer spectrum	4096
0	8	return 2048 x 32-bit integer spectrum	8192
0	16	return 4096 x 32-bit integer spectrum (default)	16384
0	32	reserved	64
0	33	return 256 x 32-bit integer spectrum + packet0	1088
0	34	return 512 x 32-bit integer spectrum + packet0	2112
0	36	return 1024 x 32-bit integer spectrum + packet0	4160
0	40	return 2048 x 32-bit integer spectrum + packet0	8256
0	48	return 4096 x 32-bit integer spectrum + packet0	16448
1	1	zero out the spectrum inside the MCA	2
2	2	stop MCA loop, go to Stop mode command processing	2
3	3	return current MCA parameters array	512
4-32	v	set parameter with byte1 index to byte2 value v	2
17	d	increment DAC by d = [-100,100]	2
122	122	return 1919 DAC integers (32-bit) recorded for each 1/16th of a degree Celsius starting from -42C (32-bit integers)	7676

When the host software sends the two-byte command [0,16] to the MCA, the MCA replies with an energy spectrum of 4096 32-bit integers, equivalent to 16,384 bytes. C code for this exchange looks like this:

```
BYTE spccmd[2] = { 0, 16 };           // cmd to request 4096x32-bit spectrum
BYTE spectrumBytes[16384];
ULONG cbWritten, cbRead;
UINT32 spectrum[4096];

if ( WinUsb_WritePipe(handle, pipout, spccmd, 2, &cbWritten, 0) )
  if ( WinUsb_ReadPipe(handle, pipin, spectrumBytes, 16384, &cbRead, 0) )
    memcpy(spectrum,spectrumBytes,16384);
```


The returned spectrum will contain the following information:

```
spectrum[0]: upper 16-bit word is number of detection events in prior interval
             lower word is 16 times the temperature of SiPMs in degrees C

spectrum[1]: accumulated count of events in channel 1

spectrum[2]: accumulated count of events in channel 2

:

spectrum[4095]: accumulated count of events in the last channel
```

The 32-bit content of spectrum[0] is determined by the feedback type parameter, stored in parameter[14] as shown in Appendix C. For the default feedback type of 0, the counts during the prior acquisition interval (CPI) is stored in the most significant 16 bits and temperature in the least significant 16 bits. For feedback type 1, the CPI in the upper 16 bits will be replaced by the current DAC level. The DAC feedback is only used during the calibration of temperature stabilization.

Table 9: Content of spectrum[0] based on feedback type.

Type	**Description of Feedback Type**	0000000000000000|0000000000000000
0	Count prior interval and temperature of SiPMs	CPI | ±°C*16
1	High voltage bias control DAC and temperature of SiPMs	DAC | ±°C*16
2	Count prior interval and baseline of SiPMs	CPI | baseline ADC
3	Count prior interval and count in capture box	CPI | n[]

A code fragment for parsing spectrum[0] for the different feedback types is given here:

```
switch ( feedbackType )      // parameter[14]
{
  case 0:                    // CPI and temperature
    cpi = (spectrum[0]>>16)&0x0000ffff;        // cpi in upper word of spectrum 0
    temp16 = (__int16)(spectrum[0]&0x0000ffff);// 16x temperature in lower word
    t = (float)t/16.0f;                        // convert to Celsius
    break;
  case 1:                    // DAC and temperature
    dac = (spectrum[0]>>16)&0x0000ffff;        // dac feedback in upper word
    temp16 = (__int16)(spectrum[0]&0x0000ffff);// 16x temperature in lower word
    t = (float)t/16.0f;                        // convert to Celsius
    break;
  case 2:                    // CPI and baseline
    cpi = (spectrum[0]>>16)&0x0000ffff;        // cpi in upper word of spectrum 0
    base = (spectrum[0]&0x0000ffff);           // ADC level in lower word
    mV = (float)base*3300.0f/4095.0f;          // convert to millivolts
    break;
  case 3:                    // CPI and n[]
    cpi = (spectrum[0]>>16)&0x0000ffff;        // cpi in upper word of spectrum 0
    npi = (spectrum[0]&0x0000ffff);            // count in box in lower word
    break;
}
```


Packet0 is a shortest data packet, containing overall counting statistics without any energy spectrum. As shown in the next code fragment, the packet0 data structure consists of sixteen 32-bit fields. The first six fields pertain to the MCA communicating with the host software via USB. The last ten fields may pertain to all of the MCAs in the array, which includes the hosted MCA and all of the other detectors that are communicating with the hosted MCA via a communication path other than USB.

```
typedef struct     // to be returned to host in response to cmd[0,0]
{
    float cps;               // 32-bit count rate of prior acquisition interval
    float totalCount;        // sum of all above threshold pulses since reset
    float totalPulseTime;    // total time in seconds inside pulses
    uint32_t usPerInterval;  // duration of most recent interval in microseconds
    uint32_t totalIntervals; // total number of intervals used to acquire data
    uint32_t capemcaId;      // the USB device id number
    uint32_t detectors;      // number of detectors in array
    float totalAcquisitionTime;// total sampling time (in seconds) since zeroed
    uint32_t countInRangeArray;// count in channel range across all detectors
    float xDirection;        // source direction based on counts in range vector
    float yDirection;
    float zDirection;
    float cpsArray;          // count across all detectors for most recent interval
    float totalCountArray;   // all above threshold pulses counted since reset
    float correctedCPSArray; // corrected count rate n from measured m
    float correctedTotalCountArray;// corrected total count N from measured M
} PACKET0_TYPE;    // sizeof(PACKET0_TYPE) = 64 bytes
```

The cps field is a 32-bit floating point number that gives the counts per second rate for the most recent communication interval. The totalCount reports the total number of radiation pulses counted since the last reset or zeroing of the MCA. Both cps and totalCount reflect all pulses detected by remaining above threshold for at least half the filter length. Many of these counted pulses are not included in the energy spectrum, either because the integral of the pulse was outside the valid channel range of [1,4095] or because they were excluded by pulse pileup rejection when it is enabled.

The next few fields provide information on the duration of actual data acquisition. The usPerInterval field is the elapsed time between onset and offset of sampling during the most recent communication interval, while the totalIntervals field tallies the number of communication intervals since the last reset or zeroing of the MCA. The totalAcquisitionTime is a more accurate measure than multiplying the totalIntervals and usPerInterval fields, but it is only present in firmware since v1.4.2.

The totalPulseTime field reports the total amount of time in seconds that the sampled signal was above threshold inside a pulse that was counted. This measures the dead time when additional pulses could not be counted. The totalPulseTime includes all counted pulses since the last reset or zeroing of the MCA. In newer versions of the firmware, the dead time and acquisition time are used to correct the counts, and these corrected values are reported in the last two fields. See the **Counting Statistics** section for details.

The capemcaId field reports the hosted MCA serial number as defined by the USB interface. The detectors field is the number of MCAs that are actively communicating in the array. When configured as an array of detectors, the hosted MCA will report the count per communication interval summed over all detectors in the cpsArray field, and report the total count from all spectra in the array for the [minChannel,maxChannel] range in the countInRangeArray field. The latter measurement includes only pulses that are included in spectra, the former includes all pulses detected. For these totals and the corrected counts, a standalone

MCA is considered an array of a single detector. The directional fields cannot be computed for a single detector, as discussed in the **MCA Arrays** section.

The packet0 structure is copied byte-by-byte into the USB communication buffer, and should be deciphered the same way on the host side, as shown in the following code fragment. When the host request is for both spectrum and packet0, the bytes are strung together in one contiguous buffer with the spectrum first and packet0 coming last. Use the expected byte-length of the spectrum to calculate where in the buffer the packet0 starts when moving the 64 bytes to the local structure representation.

```
BYTE cmd[2] = { 0, 48 };              // cmd to read 4096 spectrum + packet0
UINT32 spectrum[4096];
PACKET0_TYPE packet0;
BYTE allBytes[4096*4+64];
ULONG cbWritten, cbRead;
int bytesInSpectrum = 4096*4, bytesInPacket = 64;
int bytesToRead = bytesInSpectrum + bytesInPacket;

if (WinUsb_WritePipe(winusbHandle,pipout,cmd,2,&cbWritten,0) )
  if ( WinUsb_ReadPipe(winusbHandle,pipin,allBytes,bytesToRead,&cbRead,0) )
    {
    if ( bytesInSpectrum )            // move bytes to local spectrum array
      memcpy(spectrum,allBytes,bytesInSpectrum);

    if ( bytesInPacket )              // move packet0 bytes to local struct
      memcpy(&packet0,allBytes+bytesInSpectrum,bytesInPacket);
    }
```

When the [1,1] command is received the MCA sets the count in every channel to zero and then resumes counting pulses. The [1,1] command has a two-byte reply [1,1] which simply echoes the command. Commands with two-byte replies allow the reply to be compared to the command to validate transmission and reception. C code for commands with two-byte replies is shown in the following code box.

```
BYTE cmd[2] = { 1, 1 };               // cmd to zero out the spectrum
BYTE rply[2];
ULONG cbWritten, cbRead;

if ( WinUsb_WritePipe(handle, pipout, cmd, 2, &cbWritten, 0)
  if ( WinUsb_ReadPipe(handle, pipin, rply, 2, &cbRead, 0) )
    if ( (cbRead != 2) || (cmd[0] != rply[0]) || (cmd[1] != rply[1]) )
         printf("WARNING: USB message was garbled in Tx or Rx\n");
```

When the host software sends the two-byte command [3,3] to the MCA, the MCA replies with the array of 32-bit integers containing the 128 parameters, for 4*128=512 bytes in total.

```
BYTE cmd[2] = { 3, 3 };               // cmd to request MCA parameters
BYTE paramBytes[512];
ULONG cbWritten, cbRead;
__int32 parameters[128];

if ( WinUsb_WritePipe(handle, pipout, cmd, 2, &cbWritten, 0) )
  if ( WinUsb_ReadPipe(handle, pipin, paramBytes, 512, &cbRead, 0) )
    memcpy(parameters,paramBytes,512);
```


The returned parameter array will contain the information described in Appendix C.

Two-byte command [17,d] increments the DAC level in the MCA by:

$$DAC = DAC + d\,;$$

where d is a signed integer between -100 and 100. The reply to this command is [17,d].

Two-byte command [i,v], where i is less than 32 and not equal to 0, 1, 2, 3, or 17, executes the following statement in the MCA.

$$parameters[i] = v\,;$$

As with all two-byte replies, the command is echoed in response.

When the [2,2] command is received, the MCA loop stops running and the device listens for parameter updates of exactly 512 bytes. The parameter vector is an array of 128 32-bit signed integers which define the operating mode and calibrations of the device. The parameter vector is retained in non-volatile memory while the MCA is powered off. Parameters are loaded into RAM at power up.

The RAM values may be updated by the 2-byte host commands (listed above) or by writing the entire parameter vector from the host while the MCA loop is stopped. Additional actions are possible when the first integer (4 bytes) of the parameters message contains one of the following sequences.

Table 10: Special First Parameter in Stop Mode

Byte 1	Byte 2	Byte 3	Byte 4	Action
175	2	2	2	Read parameters from non-volatile memory
175	4	4	4	Store RAM parameters into non-volatile memory
175	7	7	7	Jump to system bootloader
175	10	10	10	Soft reset without power down
175	21	21	21	Restore factory settings from flash memory

Note that the fourth byte is the most significant byte of a 32-bit integer when the host transmission is from an Intel-based Windows PC. The MCA (ARM Cortex M7 processor) receives the individual bytes of the 32-bit integer in little endian order with the least significant byte first.

<< All commands in Stop mode must be 512 bytes in length >>

Only parameters arrays which are exactly 512 bytes in length are processed by the MCA in Stop mode, even when the first parameter contains a special command. The special command will not be processed until all 512 bytes have been received. All 512-byte commands which do not contain a special first parameter are considered to be valid parameter arrays and are copied to the MCA parameters in RAM. The host software code fragment for writing to the MCA in Stop mode is simply this:

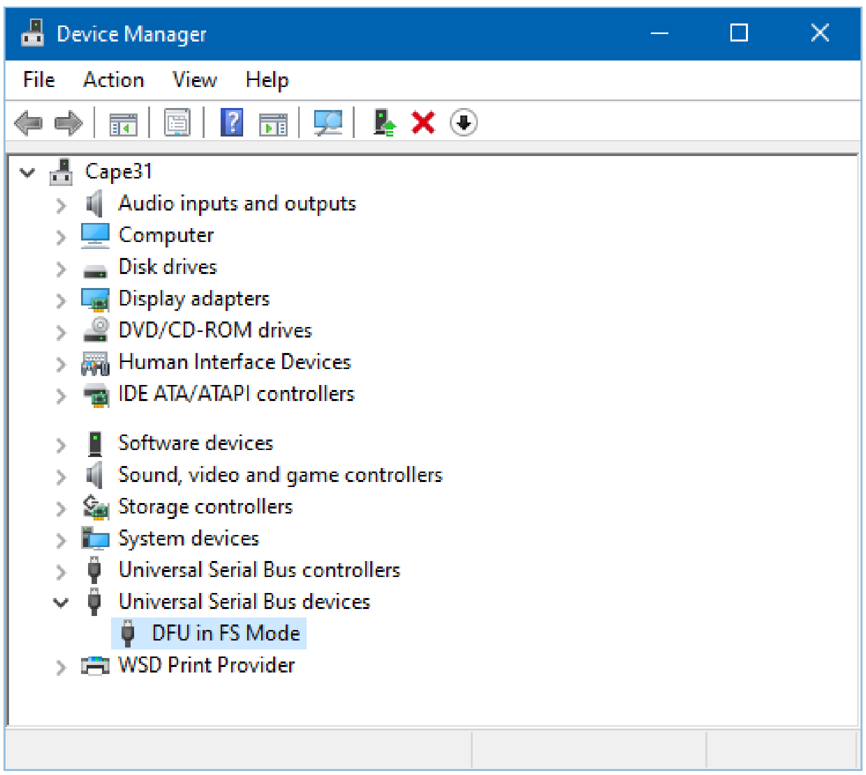
```
int parameters[128];
ULONG cbWritten;

WinUsb_WritePipe(handle, pipout, (PUCHAR)parameters, 512, &cbWritten, 0);
```

<< There is no reply to host input in Stop mode >>

When any two-byte command is received in Stop mode, the MCA run loop is immediately restarted so the command can be processed at the next communication interval. The MCA remains in Run mode accumulating a spectrum and processing two-byte commands from the host, until the host issues a two-byte command to return to Stop mode.

In Stop mode, a soft reset of the MCA can be generated by setting the first 32-bit parameter to the four-byte sequence [175,10,10,10]. This will return the MCA to its initialization state without requiring that the device be disconnected from power. However, if the USB connection has become corrupted, a power-on reset may be the only way to recover normal operation.

When the bootloader is invoked, the MCA resets to Device Firmware Update (DFU) programming mode, in which an external programmer (such as the STM32 Cube Programmer) may be used to erase and rewrite the MCA firmware.



In DFU mode, the WinUSB driver is unloaded from the Device Manager and a new driver appears, the *DFU in FS Mode*. Therefore it is no longer possible to restart the MCA loop without a power-on reset. Power-on reset requires that the USB cable be disconnected.

<u>WARNING:</u> If the RDP level was elevated after factory programming, the entire MCA flash memory will be erased by any attempt to connect to it with the STM32 Cube Programmer. At which point, the MCA will no longer work without completely reprogramming it, if that is even possible. Depending on the RDP level and hardware configuration, attempting to connect to the *DFU in FS Mode* might cause the MCA to permanently stop working and make it irreparable!

Appendix B: File Formats

As noted above, the default format expected when using Auto Save and Auto Load is the comma separated values format. These files may or may not contain a channel zero, but if present channel zero will have a floating point value representing the temperature in Celsius. When saving a spectrum directly using the *Save Spectrum As* dialog, there will be no channel zero. An example is displayed in the next box.

```
1,0
2,0
3,4
4,8
5,5
6,3
7,7
8,3
9,5
10,2
11,7
:
4090,0
4091,0
4092,0
4093,0
4094,0
4095,0
```

SPE Spectrum File:

SPE format files are also ASCII text files with fields before the spectrum data delimited by fixed keywords beginning with $ in column 1.

```
$SPEC_ID:
C:\Temp\spectrum.spe
$SPEC_REM:
Packet0 feedback required for live, dead, real times.
$DEVICE_ID:
CapeMCA
SN# 0
HW# 1.0.75
FW# 1.3.6
$DATE_MEA:
02/01/2024 10:36:50
$MEAS_TIM:
0 0
$ENER_FIT:
0 0.0178571 0
$RT:
0
$DT:
0
$PUR:
off
:
```



```
$DATA:
1 2047
         0
         0
         0
         0
         0
         0
         5
       137
         :
         0
         0
$TEMPERATURE:
25.1875
$TS:on
```

CHN Spectrum File:

CHN format files normally contain a sequence of binary integers intermixed with ASCII characters. This is simplified here to a header sequence of 16 two-byte binary integers followed by the spectrum stored as a sequence of binary 32-bit integers. There are no line terminations, but the example here uses separate lines for clarity of the individual values.

```
-1
0
0
0
0
0
0
0
0
0
0
0
0
0
0
4095
0
:
0
```

N42 Spectrum File:

The N42 file format is a minimal XML document adhering to the ANSI N42.42 schema, currently available online at "https://www.nist.gov/document/n42xsd". The ANSI schema is too big to reproduce here, but a copy is provided by the CapeMCA installer. The file format for representing spectra AND packet0 data is defined by extending the N42.42 standard. These extensions are defined in the following capemca.xsd.

```
<?xml version="1.0" encoding="UTF-8"?>
<xsd:schema targetNamespace="capemca"
            xmlns:n42="http://physics.nist.gov/N42/2011/N42"
            xmlns:xsd="http://www.w3.org/2001/XMLSchema"
            elementFormDefault="qualified">
  <xsd:import namespace="http://physics.nist.gov/N42/2011/N42"
schemaLocation="n42.xsd"/>

  <xsd:element name="TemperatureCelsius" type="xsd:double"
substitutionGroup="n42:SpectrumExtension"></xsd:element>
  <xsd:element name="SpectrumType" type="xsd:nonNegativeInteger"
substitutionGroup="n42:SpectrumExtension"></xsd:element>

  <xsd:element name="countsPerSecond" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalCount" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalPulseTime" type="xsd:duration"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="usPerInterval" type="xsd:nonNegativeInteger"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalIntervals" type="xsd:nonNegativeInteger"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="capemcaId" type="xsd:integer"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="detectors" type="xsd:positiveInteger"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalAcquisitionTime" type="xsd:duration"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="countInRangeArray" type="xsd:nonNegativeInteger"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="xDirection" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="yDirection" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="zDirection" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="cpsArray" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalCountArray" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="correctedCPSArray" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="correctedTotalCountArray" type="xsd:double"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <!-- the following elements are deprecated and will no longer be supported -->
  <xsd:element name="cpiArray" type="xsd:nonNegativeInteger"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalPulseTimeArray" type="xsd:duration"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
  <xsd:element name="totalLiveTimeArray" type="xsd:duration"
substitutionGroup="n42:RadMeasurementExtension"></xsd:element>
</xsd:schema>
```

Note that .n42 files may be validated against the extended standard, but both of the .xsd schema files that define the format have to be stored in the same folder as the .n42 file. Here is an example .n42 output:

```xml
<?xml version="1.0"?>
<RadInstrumentData xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
  xmlns="http://physics.nist.gov/N42/2011/N42" xmlns:capemca="capemca"
  xsi:schemaLocation=
"http://physics.nist.gov/N42/2011/N42 n42.xsd capemca capemca.xsd" >
  <RadInstrumentInformation id="MCA1">
    <RadInstrumentManufacturerName>CapeSym Inc</RadInstrumentManufacturerName>
    <RadInstrumentModelName>CapeSym MCA</RadInstrumentModelName>
    <RadInstrumentClassCode>Other</RadInstrumentClassCode>
    <RadInstrumentVersion>
      <RadInstrumentComponentName>Firmware</RadInstrumentComponentName>
      <RadInstrumentComponentVersion>1.4.5</RadInstrumentComponentVersion>
    </RadInstrumentVersion>
  </RadInstrumentInformation>
  <RadDetectorInformation id="Detector">
    <RadDetectorCategoryCode>Gamma</RadDetectorCategoryCode>
    <RadDetectorKindCode>Other</RadDetectorKindCode>
  </RadDetectorInformation>
  <EnergyCalibration id="EC0">
    <CoefficientValues>0.0 0.000310945 0.0</CoefficientValues>
    <Remark>y = quadratic(x) where x is the integral of pulse</Remark>
  </EnergyCalibration>

  <RadMeasurement id="M1">
    <MeasurementClassCode>Foreground</MeasurementClassCode>
    <StartDateTime>2025-03-17T14:53:49</StartDateTime>
    <RealTimeDuration>PT302.687000S</RealTimeDuration>
    <Spectrum id="S1" energyCalibrationReference="EC0">
      <LiveTimeDuration>PT300.794119S</LiveTimeDuration>
      <ChannelData compressionCode="None">
         4
        12
         :
         2
      </ChannelData>
      <capemca:TemperatureCelsius>25.1875</capemca:TemperatureCelsius>
      <capemca:SpectrumType>6</capemca:SpectrumType>
    </Spectrum>
    <capemca:countsPerSecond>65.0375</capemca:countsPerSecond>
    <capemca:totalCount>20768</capemca:totalCount>
    <capemca:totalPulseTime>PT0.0325046S</capemca:totalPulseTime>
    <capemca:usPerInterval>999424</capemca:usPerInterval>
    <capemca:totalIntervals>301</capemca:totalIntervals>
    <capemca:capemcaId>288</capemca:capemcaId>
    <capemca:detectors>1</capemca:detectors>
    <capemca:totalAcquisitionTime>PT300.826S</capemca:totalAcquisitionTime>
    <capemca:countInRangeArray>0</capemca:countInRangeArray>
    <capemca:xDirection>0</capemca:xDirection>
    <capemca:yDirection>0</capemca:yDirection>
    <capemca:zDirection>0</capemca:zDirection>
    <capemca:cpsArray>69.0367</capemca:cpsArray>
    <capemca:totalCountArray>20768</capemca:totalCountArray>
    <capemca:correctedCPSArray>69.0441</capemca:correctedCPSArray>
    <capemca:correctedTotalCountArray>20770.2</capemca:correctedTotalCountArray>
  </RadMeasurement>
</RadInstrumentData>
```

In the example .n42 file shown above, N42 recording was set to 300s of live time, as reflected in the <LiveTimeDuration> element. When the actual real time duration or live time is not known (e.g. because packet0 information was not included in the spectrum request type), values of zero will appear in these elements. The packet0 extension data will only appear when the *Request # of channels* includes the packet0 data.

The elements that begin with "<capemca:" are extensions provided by the aforementioned capemca.xsd schema. Such extensions are necessary for temperature and packet0 fields because the basic N42 standard has no equivalent definitions. In fact, the N42 standard is designed to support only the recording of energy spectra. No provisions are made for recording other types of channel data. However, CapeSym's MCAs are capable of returning many different types of channel data, some of which are important for calibration and validation of the instrument, so an additional N42 spectrum extension is provided to recover the spectrum type. The <SpectrumType> element is an integer that records the MCA's spectrum type parameter, as shown in the above example.

Appendix C: MCA Parameters

The MCA contains 128 parameters stored as 32-bit signed integers. Optimal parameters are different for each unit (MCA electronics and detector). The parameter table for particular sensor unit is available in the MCA Parameters dialog, or from the console menu. Older firmware versions may use a slightly different set of parameters than shown here, because of changes to the feedback options or the energy correction algorithm.

Index	Value	Description
0	1	Major version
1	1	Minor version
2	11	Release version
3	56	Divisor for integral to channel
4	0	Pulse pileup rejection on/off
5	1	Temperature stabilization (TS) on/off
6	0	Spectrum type: 0=count/chan, 1=width/chan, 2=ADC/sample, 3=pulse list, 4=test...
7	1	Energy correction (EC) on/off
8	1	Detector index in array
9	0	Moving spectrum off/moving/shared
10	32	Depth of moving spectra [0,32] or [0,20] or [0,16]
11	10	Communication interval [1,100]*100ms
12	4	Pulse threshold in ADC levels (14-bit 4.96/mV | 12-bit 1.24/mV)
13	2035	DAC [0,4095] determines high voltage when TS is off at reset
14	0	Feedback type: 0=cpi+temp, 1=DAC+temp, 2=cpi+baseline, 3=cpi+n[]
15	10	Min. channel of range-limited operations, e.g. sample buffer
16	4095	Max. channel of range-limited operations, e.g. source direction
17	0	Peak target for DAC servo, disabled when zero
18	2000	Capture box [] left channel
19	3500	Capture box [] right channel
20	20	Capture box [] top pulse width deficit
21	80	Capture box [] bottom pulse width deficit
22	0	Independent watchdog reset on/off
23	-1	Pulse decay rate compensation in number of samples
24	-1	Pulse filter width in number of samples
25	-1	Log current monitor 100000*slope
26	-1	Log current monitor 100000*y_intercept
27	-1	Reserved for future use
28	0	Energy correction curve fit coefficient 1
29	0	Energy correction curve fit coefficient 2
30	0	Energy correction curve fit coefficient 3
31	0	Energy correction curve fit coefficient 4
32	-402895	Pulse width curve fit coefficient 1
33	61	Pulse width curve fit coefficient 2
34	-6586	Pulse width curve fit coefficient 3
35	281313	Pulse width curve fit coefficient 4

36	10	Offset from curve to pulse width lower limit
37	10	Offset from curve to pulse width upper limit
38	4	Number of temperature stabilization lines (6 max.)
39	92	Line 1: 16*temperature at start of line segment
40	1220	Line 1: 100*slope of line
41	2846190	Line 1: 1600*y-intercept of line
42	336	Line 2: 16*temperature at start of line segment
43	1700	Line 2: 100*slope of line
44	2684800	Line 2: 1600*y-intercept of line
45	416	Line 3: 16*temperature at start of line segment
46	1667	Line 3: 100*slope of line
47	2698667	Line 3: 1600*y-intercept of line
48	560	Line 4: 16*temperature at start of line segment
49	1889	Line 4: 100*slope of line
50	2574222	Line 4: 1600*y-intercept of line
51	-1	Line 5: 16*temperature at start of line segment
52	-1	Line 5: 100*slope of line
53	-1	Line 5: 1600*y-intercept of line
54	-1	Line 6: 16*temperature at start of line segment
55	-1	Line 6: 100*slope of line
56	-1	Line 6: 1600*y-intercept of line
57	0	Number of calibrated energy integrals (35 max.)
58	-1	Energy 1
59	-1	Integral or channel
60	-1	Energy 2
61	-1	Integral or channel
62	-1	Energy 3
63	-1	Integral or channel
64	-1	Energy 4
65	-1	Integral or channel
66	-1	Energy 5
67	-1	Integral or channel
68	-1	Energy 6
69	-1	Integral or channel
70	-1	Energy 7
71	-1	Integral or channel
72	-1	Energy 8
73	-1	Integral or channel
74	-1	Energy 9
75	-1	Integral or channel
76	-1	Energy 10
77	-1	Integral or channel
78	-1	Energy 11
79	-1	Integral or channel
80	-1	Energy 12
81	-1	Integral or channel
82	-1	Energy 13
83	-1	Integral or channel

84	-1	Energy 14
85	-1	Integral or channel
86	-1	Energy 15
87	-1	Integral or channel
88	-1	Energy 16
89	-1	Integral or channel
90	-1	Energy 17
91	-1	Integral or channel
92	-1	Energy 18
93	-1	Integral or channel
94	-1	Energy 19
95	-1	Integral or channel
96	-1	Energy 20
97	-1	Integral or channel
98	-1	Energy 21
99	-1	Integral or channel
100	-1	Energy 22
101	-1	Integral or channel
102	-1	Energy 23
103	-1	Integral or channel
104	-1	Energy 24
105	-1	Integral or channel
106	-1	Energy 25
107	-1	Integral or channel
108	-1	Energy 26
109	-1	Integral or channel
110	-1	Energy 27
111	-1	Integral or channel
112	-1	Energy 28
113	-1	Integral or channel
114	-1	Energy 29
115	-1	Integral or channel
116	-1	Energy 30
117	-1	Integral or channel
118	-1	Energy 31
119	-1	Integral or channel
120	-1	Energy 32
121	-1	Integral or channel
122	-1	Reserved for future use
123	16383	Maximum ADC level
124	115200	Serial UART interface baud rate in Hz
125	5555556	Hardware sample rate in Hz
126	16793088	Hardware version number: e.g. 0x01.00.4B.00
127	0	Energy correction table type (0 => quadratic fit)

Appendix D: Host Code Examples

Source code for a command line program to read from the MCA using the WinUSB API in Visual C++ is provided by the CapeMCA Windows installer, typically in the folder C:\Program Files\CapeMCA\example. The code includes a C++ wrapper for the WinUSB device interface and a build file for the Visual C++ nmake utility. The application can be built from the Windows command prompt using

```
> nmake /f capeMCAcli.mak
```

and run by

```
> capeMCAcli
```

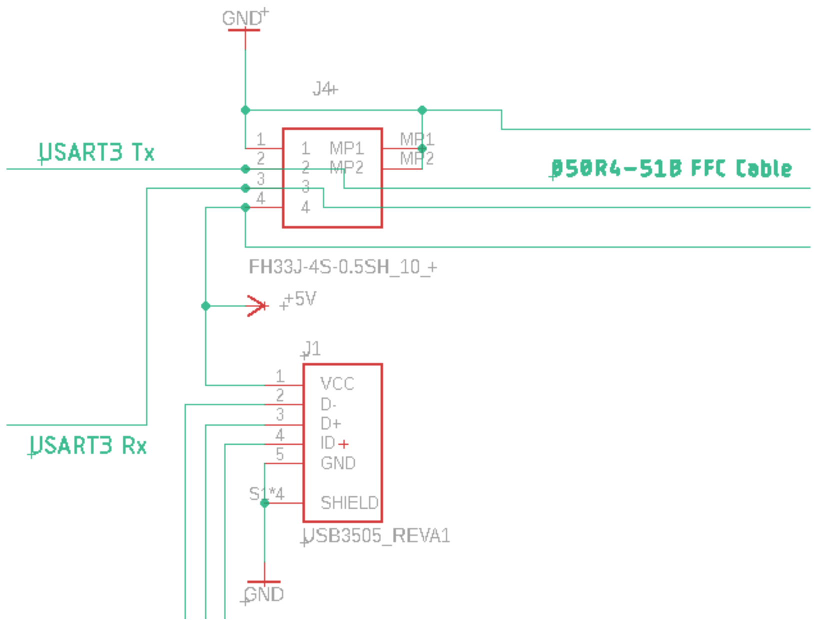
```
Enumerating MCAs... found 1 MCAs

Connecting to MCAs

1: capemca00060 : connected

Requesting spectra from MCAs

Reading spectra from MCAs
Spectrum 1:
channel,count
1,0
2,0
3,0
4,92
5,915
6,1625
:
4093,0
4094,0
4095,0

Done.
```

The program will search for and connect to any MCAs that have been plugged into the computer's USB ports. Then the program will read the spectrum from each device, sum the spectra together, and output the total count for each channel, as show in the above output.

The USB interface to the MCA can alternatively be accessed by using the libusb library. This would be a convenient way to communicate with the MCA from a Linux computer, and example code is also provided to demonstrate how to access the MCA from the Linux operating system.

Appendix E: Serial UART Interface

Version 1.0.62 of the MCA hardware includes an FFC connector to support a serial interface in addition to the USB bulk transfer device interface. The USB interface with microB connector allows a host computer to configure the MCA operating parameters. When no USB data lines are detected, the alternative serial interface will become active, over which spectral data may be requested and sent at every communication interval. The serial interface will transmit the same data packet that is normally sent in response to the two-byte request {0,n} via the USB interface.



The pinout of the FFC connector (0.5 mm pitch) is diagrammed in the above figure. The serial interface is provided by the USART3 communication peripheral of the STM32H743 microcontroller operating in the default full-duplex asynchronous mode at 3.3V with 1 stop bit, 1 start bit, 8 data bit, and no parity. Baud rates of up to 2.88Mbit per second are selectable through the baud rate parameter (index=124). The baud rate parameter may be saved to non-volatile memory from a host computer using the USB interface.

Power to the MCA can be provided by either the USB microB connector or on the 4-pin FFC connector (part: FH33J-4S-0.5SH(10) Hirose Electric). The v1.0.62 MCA with UART interface expects 5V input, but it has its own 3.3V regulator (MCP1755S) so any input voltage between 3.6 and 5V will work.

The serial UART interface listens for data requests from the host computer on the Rx line, and processes 1 command per communication interval. The two-byte command and variable length response format is the same as employed by the USB interface, as detailed in the following table. Note that Stop mode is not accessible via the serial UART interface, so any calibrations and parameter settings will need to done through the USB interface first.

Byte 1	Byte 2	Command	Reply Bytes
0	0	return packet0 data structure	64
0	1	return 256 x 32-bit integer spectrum	1024
0	2	return 512 x 32-bit integer spectrum	2048
0	4	return 1024 x 32-bit integer spectrum	4096
0	8	return 2048 x 32-bit integer spectrum	8192
0	16	return 4096 x 32-bit integer spectrum (default)	16384
0	32	reserved	64
0	33	return 256 x 32-bit integer spectrum + packet0	1088
0	34	return 512 x 32-bit integer spectrum + packet0	2112
0	36	return 1024 x 32-bit integer spectrum + packet0	4160
0	40	return 2048 x 32-bit integer spectrum + packet0	8256
0	48	return 4096 x 32-bit integer spectrum + packet0	16448
1	1	zero out the spectrum inside the MCA	2
4-32	v	set parameter with byte1 index to byte2 value v	2
17	d	increment DAC by d = [-100,100]	2

Source code for an example command line program to read from the MCA using the Win32 serial port API in Visual C++ is provided by the CapeMCA Windows installer. The code includes a build file for the Visual C++ nmake utility. The application can be built from the Windows command prompt using

```
> nmake /f capeMCAuart.mak
```

and run by

```
>capeMCAuart -?

CapeMCA Uart Interface

Usage: CapeMCAuart [flags]

Flags:
  -b=115200 : use baud rate 115200 bit/s (default)
  -p=COM1 : use COM1 for serial port (default)
  -q=8 : request type {0,1,2,4,8,16,32+1,32+2,32+4,32+8,32+16}
  -h : display this help message
  -v : print version info
  -z : zero spectrum before request

Read energy spectrum from 1 macropixels via COM port.
Spectral output is streamed to the console.
```

