System theremino

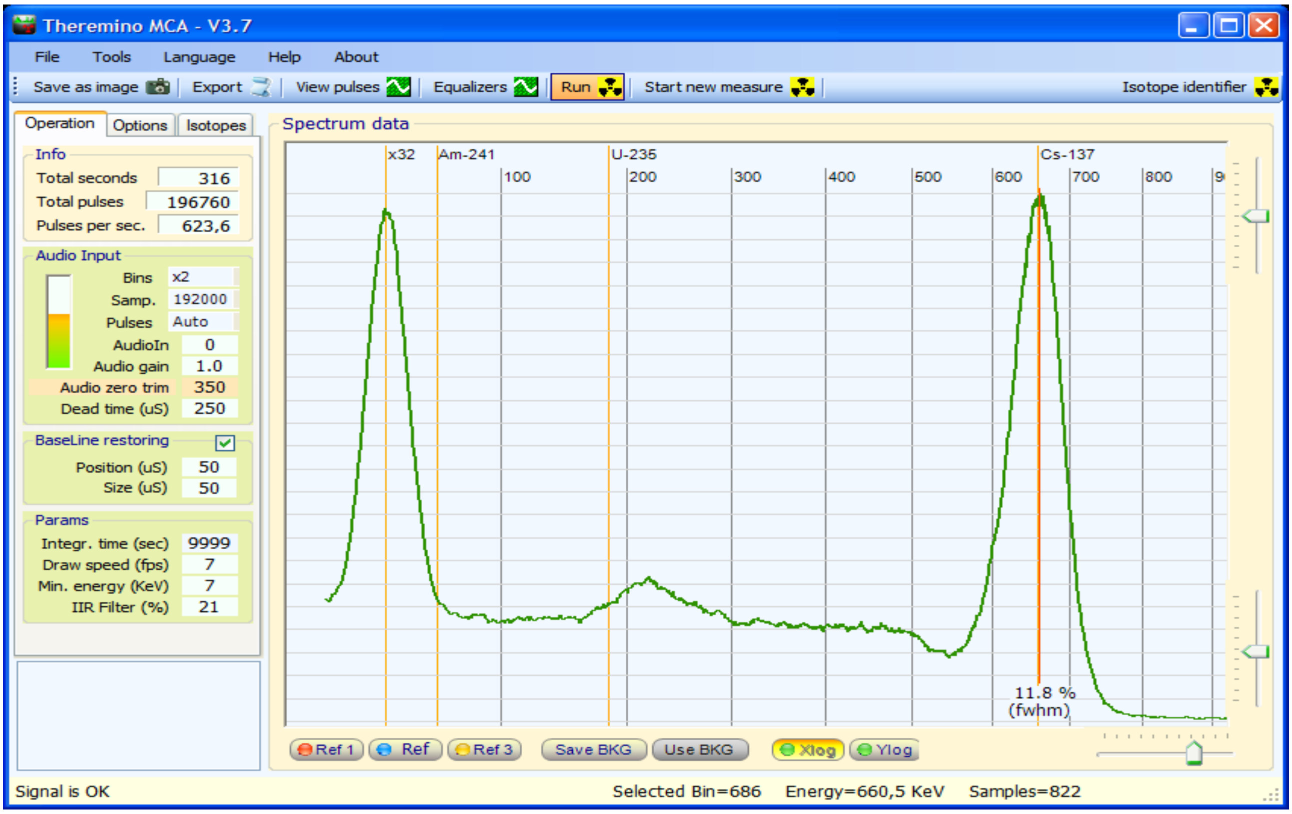
Techniques of signal conditioning for Gamma Spectrometry

Gamma Spectrometry

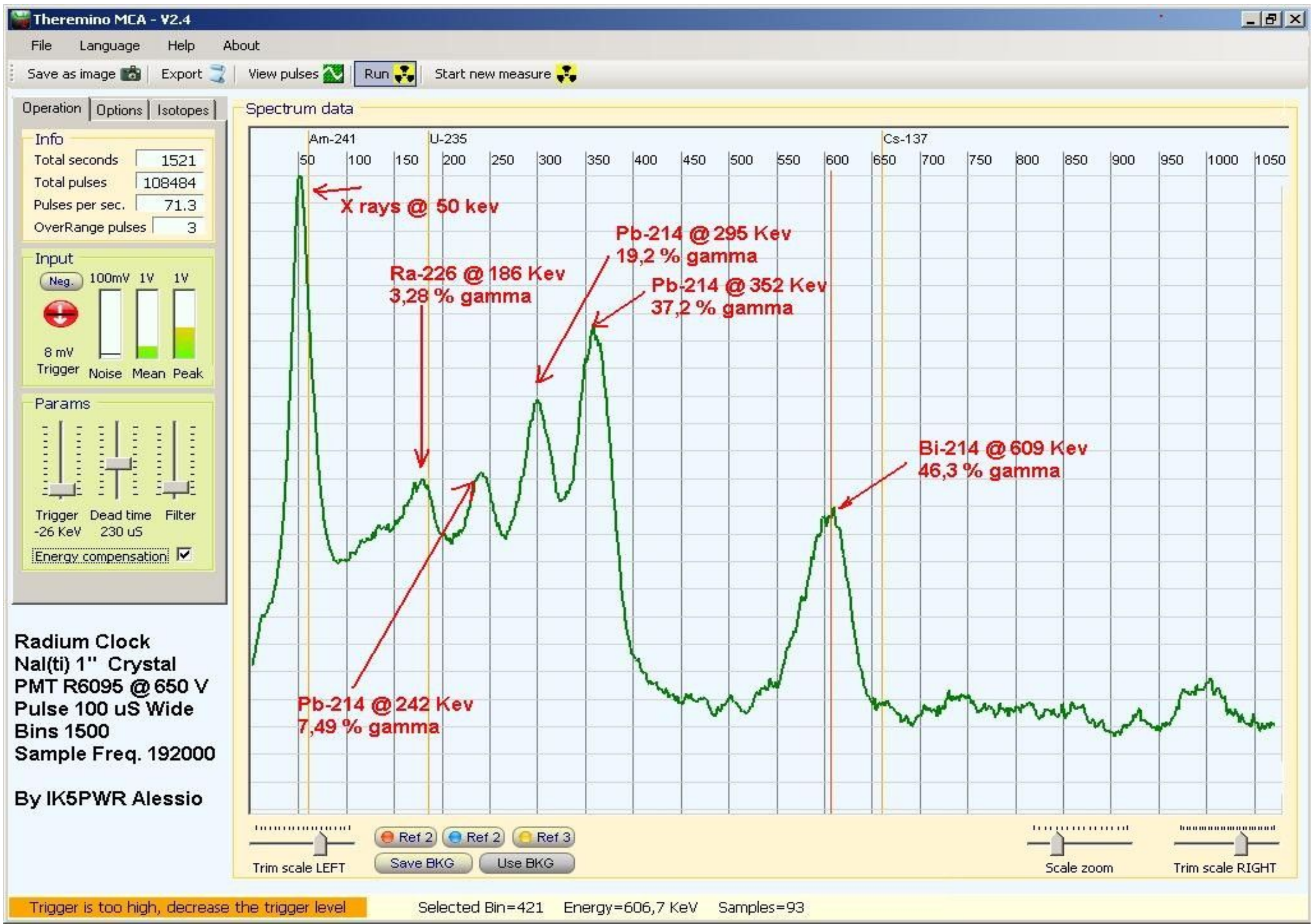
By measuring the spectrum of energies it is possible to distinguish radioactive isotopes and appreciate their relative abundance. Each isotope produces gamma rays with energy focused on one or more lines. The shape of the resulting graph is a kind of "signature" that is used to detect radioactive substances present in the sample under test.

The single gamma rays are detected by sensors (crystal scintillators, photo-multiplier tubes, and photo-diodes) and transformed into electrical impulses at a rate proportional to the energy of the gamma ray, normally measured in KeV (Kilo ElettronVolt)

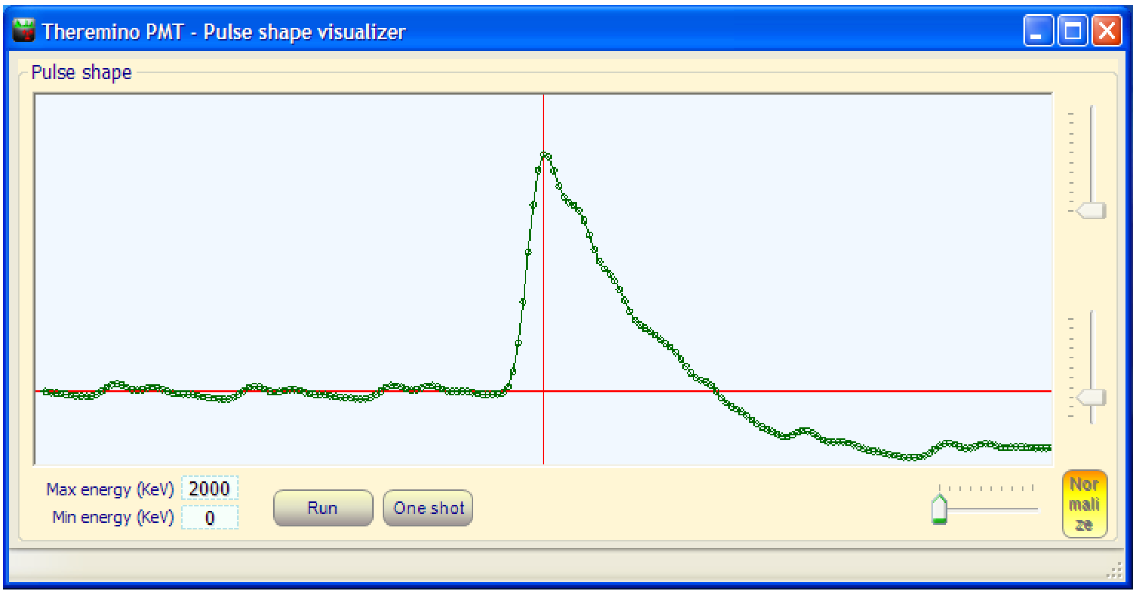
With special software called MCA (Multi Channel Analyzer) pulses are extracted from the noise and transformed into graphs, calibrated in keV, that can be easily read by an operator.



This is the "signature" of radioactive cesium (Cs-137), easily recognizable and therefore much used for calibration. Other "signatures" well known to experts in the field are those of americium (Am-241), the Radio (Ra-226), the cobalt (Co-60) and Potassium (K-40)



This is the "signature" of the Radio (Ra-226), with its four characteristic peaks at 186, 242, 296 and 352 keV and a single peak at 609 keV



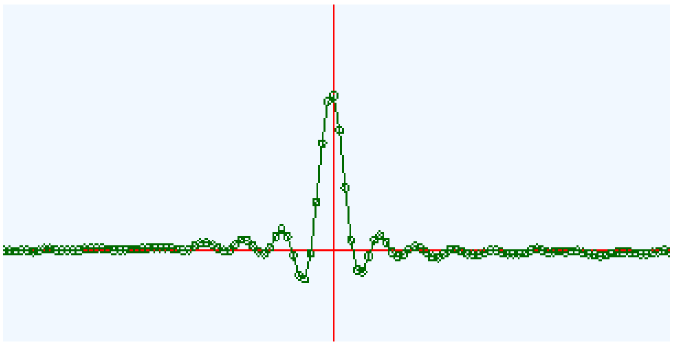
This is a pulse coming from a crystal scintillator coupled to a photo-multiplier tube and amplified.

Recognize the pulses

The recognition of the pulses is crucial to a multichannel analyzer, there are many ways to do this, they all work well on the pulse of high energy, but few are able to work well in the area of very low energies.

The well-known software PRA, for example, uses the recognition of pulse shape "Shape recognition" that works pretty well, but it eliminates a large number of pulses and noticeably slows down the display.

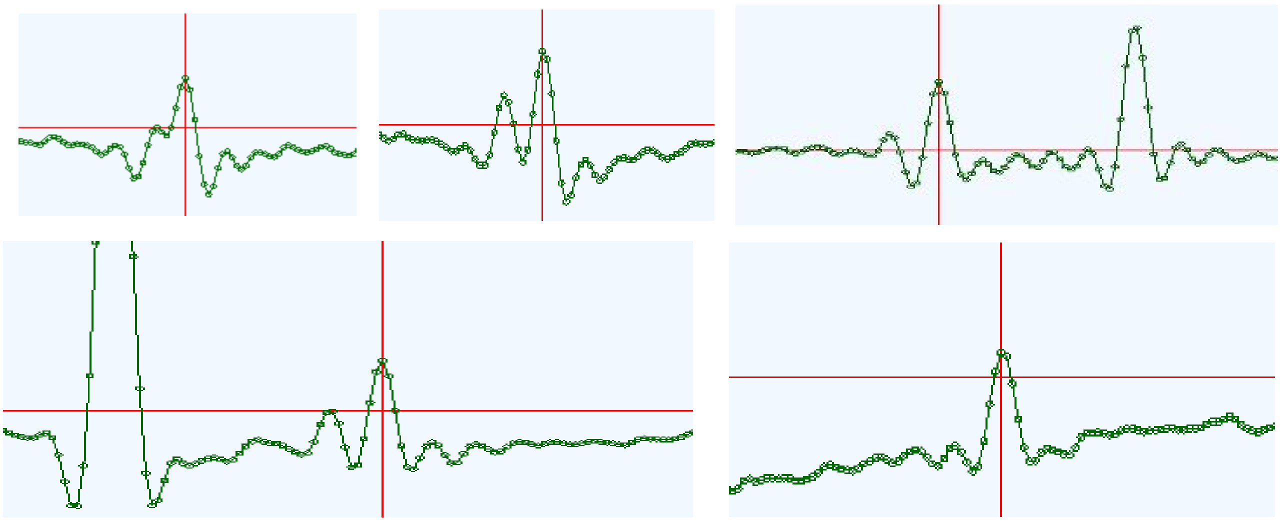
Intuitively you think that recognize the impulses of the form is the ideal method. This is true when the pulses are high but they are small, deformed from noise and "ringing" this method can only do one thing, delete them.



We do realize that you have in the "Shape" to recognize the pulse of the image on the left. In general, high-energy pulses will be more or less similar and "Shape Recognition" will recognize them easily.

But what made the pulses are very low, with energies below 100 keV?

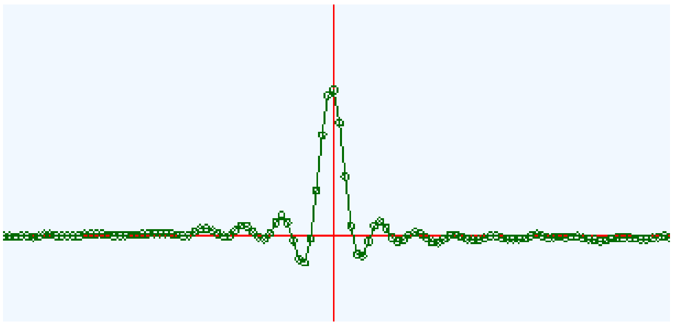
Here's some - attention that the scale of any future images was amplified very vertical, actually pulses are 10 to 100 times lower than the previous.

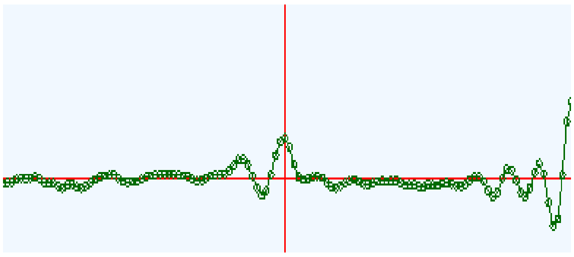


They are all distorted by noise, not if it finds one that looks like those high energy. In this situation the "Shape recognition" can do only two things, or delete them all, or is satisfied with a distant resemblance to good and takes all the "ringing" and all the little bumps that look like a noise pulse producing a mountain of noise on the left side of the graph covering, move and blur the lines of interest.

How Theremino MCA recognizes the pulses

As seen in the previous page, the "Shape recognition" is slow and produces a lot of noise but there is a better method?





Pulse of high-energy (660 keV) Pulse of very low energy (32 keV)

A human, looking at these two images immediately recognizes that even one on the right is a valid pulse, even if of completely different shape.

Even Theremino MCA succeeds, in fact, the red line indicates which took him perfectly in the center, if the signal is reasonably free of noise, the Theremino MCA recognizes them without error, as you can see with his "Pulse shape visualizer"

To reach this result, the Theremino MCA uses a set of "behavioral" techniques, that are based not on the form, which can vary, but about how a pulse behaves differently from the noise.

First of all it is necessary to predict the future ... that is, to have even those who have not yet arrived, to do this you pass all the momentum in a delay line (a circular buffer) and then read the pulses but not when they occur some time after. In this way it is possible to have the characteristics of the area following the pulse.

Then check the main features: What is the highest sample of this impulse? There are samples higher nearby? There are other pulses superimposed? The zero line is in place or is lower or higher? What looks like a pulse will probably just noise?

Then you try to correct everything possible to erase the effects of the "ringing" and noise and straighten the zero line.

Finally, if all goes well, you store the boost otherwise you delete it.

The rate of elimination of ThereminoMCA is minimal, almost "not miss a beat" and this shows the rate of creation of his graphs.

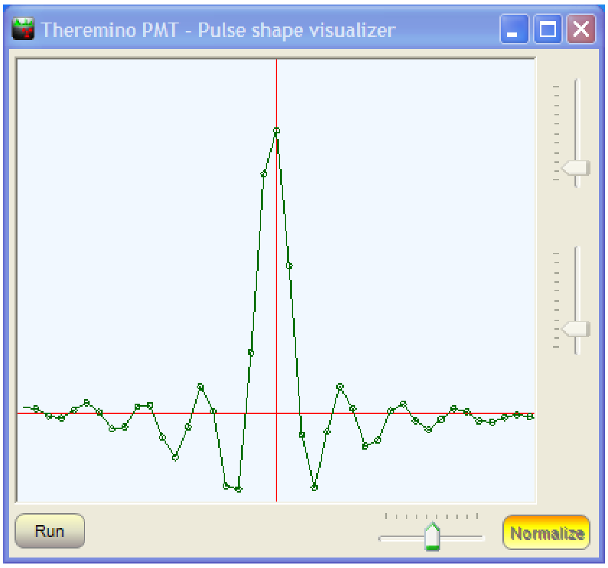
Audio signal, sampling and "ringing"

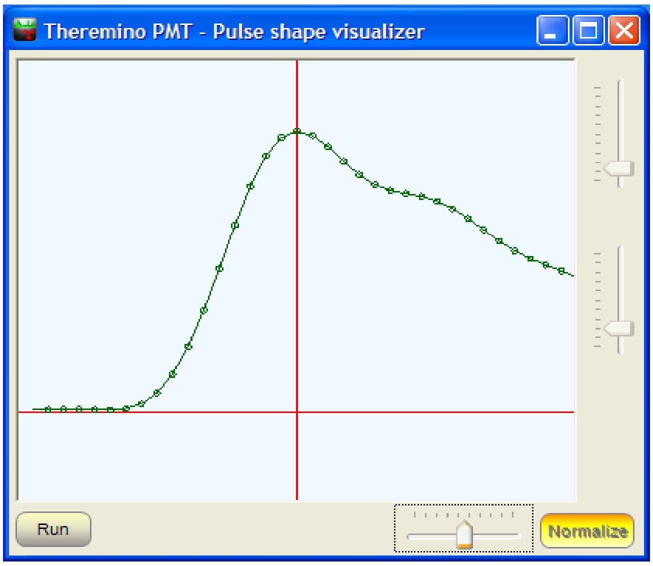
The ringing (that means "vibration" or "resonance") is created by the anti-aliasing filter of the sound card.

Many people thinks that the ringing depend on the cables or amplifier signal and try to act on these components to eliminate it, without success.

To eliminate the ringing must soften the pulses with an appropriate low-pass filter that lengthen the few micro seconds products from the photo-multiplier tube to at least 100 uS

Lengthening the pulse if you lose someone, but during normal laboratory measures not if you lose a small percentage and this loss is compensated by having more accurate and readable pulse so that the speed but increases rather than diminishes greatly.



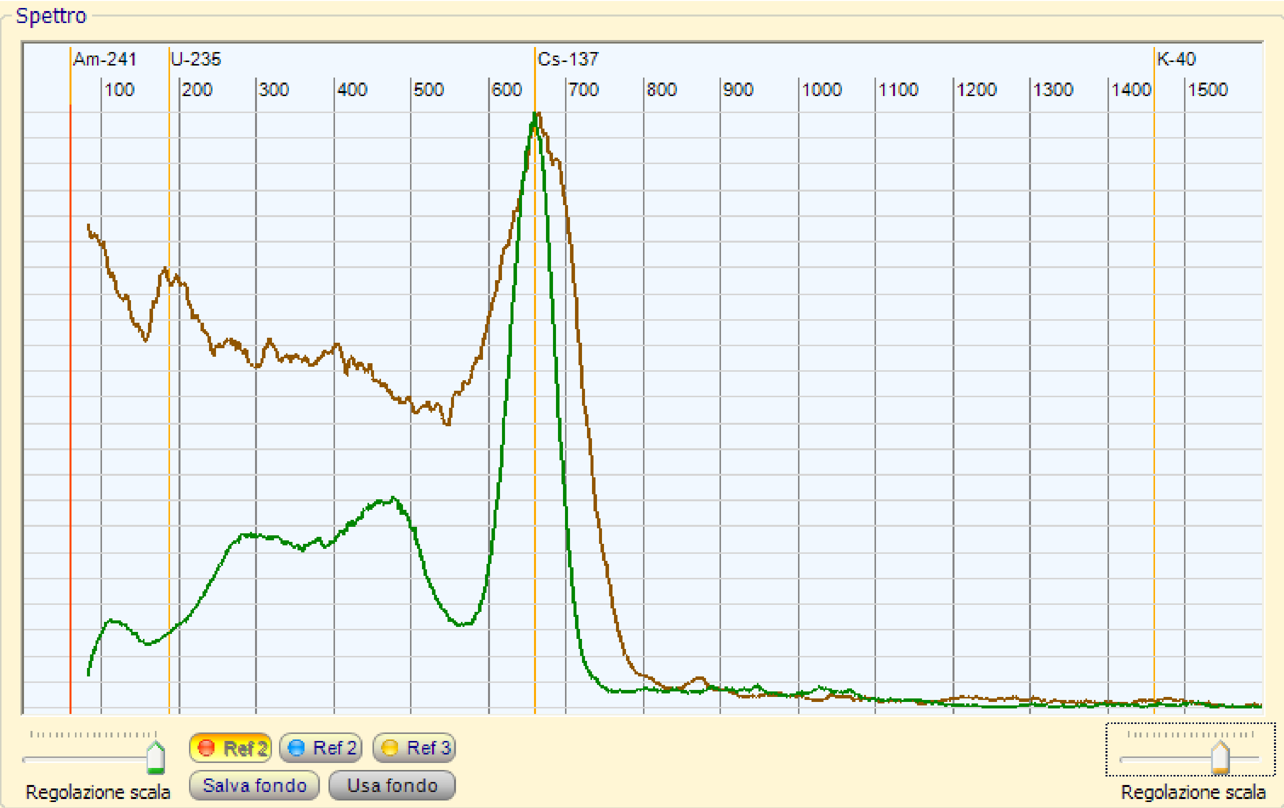


Picture 1 - 10 uS pulse from Picture 2 - Pulse to 100 uS

In the image "1" you will see a very narrow pulse (10 uS), which produces a loud "ringing" while the "2" you will see a boost from 100 uS that does not produce "ringing"

Note also that in the first image the maximum point is sampled poorly, with too few points, resulting in inaccurate measurement that widen considerably the lines as shown on the next page.

Unfiltered signals



The line of cesium - in red with 10 uS pulses, green pulses with 100 uS

In this image we see an unfiltered signal (in red) that produces a considerable enlargement of the row of cesium and an increase in the carpet of noise that rises up to get rid of the two humps characteristics at about 300 and 450 KeV

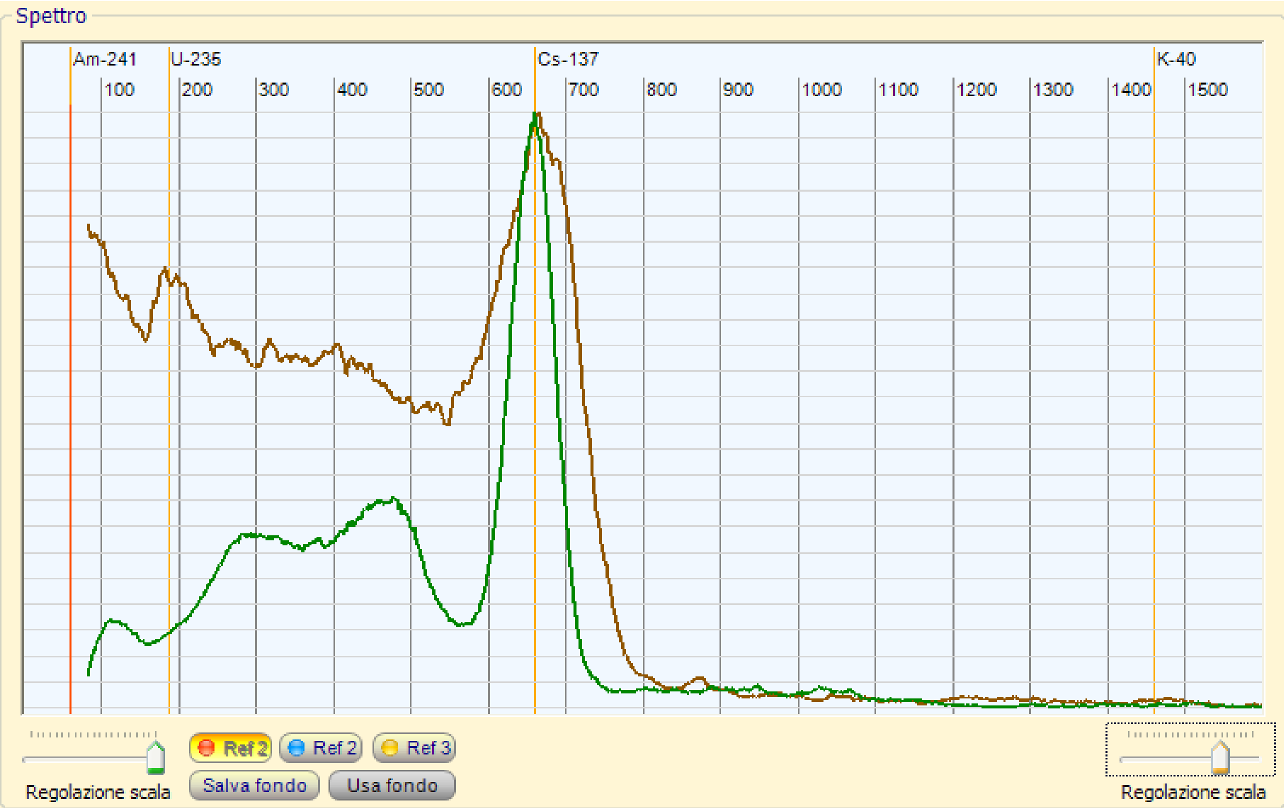
Extending the pulse sharpens the sampled values, tightening the lines of the isotopes, reduces noise and it pop even the weakest signals.

Using enlarged pulses has only benefits and no side effects. Under normal measures are measured frequencies around 100 cps then the average distance between two pulses is about 10 milliseconds. Ten milliseconds is 100 times greater than 100us. For which you lose very few pulses due to the PileUp effect.

Even with very large pulses (up to 500 uS) do not occur measurement errors caused by "Pile up" because in these cases the software eliminates the second pulse.

Often someone objects that sometimes measure samples very radioactive and that in these cases the pulses are more frequent, even 10,000 per second, resulting in losing a lot. The reasoning is not wrong, in which case you lose as much as 50% of the pulses. But it does not matter because you have the same so frequent pulses that a perfect curve is created in a few seconds.

Causes of the enlargement of the lines



In "red: a significant enlargement of the cesium line, in green a modest enlargement.

Many mechanisms contribute to enlarge the spectral lines, the most important are:

- The material of the scintillator
- The geometry, transparency and the surface finish of the scintillator
- The reflection and refraction of light in the path between the crystal and the PMT tube cathode
- Noise and "ringing" that distort the signal.
- Errors of discrimination between pulses and noise
- Movements of the zero line pulse ("Base line shifting")
- Systematic errors in the measurement software

All of these mechanisms produce similar errors, mainly the following:

(1) Enlargement of the line
(2) Lowering of the tip of the line. In this image the line of cesium was normalized for which this effect is not visible.
(3) Raising of the base line to the left of the lines
(4) Raising of the base line to the right of the rows (of lesser magnitude than the previous)

Why the crystal expand the lines?
And why widen more to the left?

The crystals scintillators convert the gamma photons into photons of visible light, while converting each photon range is multiplied in a number of photons of light.

The number of photons of visible light produced by each gamma photon depends on the ratio between the frequencies of the two photons (or the ratio of energy that ultimately is the same thing)

For example, a photon range from 660 keV (Cs) is expected to produce about 330 thousand photons of visible light blue-green and a photon of 32 keV (Americium) produce 16 000. Given, however, becuase the crystals have an efficiency a little 'less than 10%, in the first case will be about twenty five thousand and in the second approximately one thousand.

Photon	Wavelength	Energy (approx)
Gamma rays	0.0001 nm 0.01 nm	10 MeV 100 KeV
X-ray	0.01 nm 10 nm	100 KeV 0.1 KeV (100 eV)
Visible light yellow	400 nm	0.0025 KeV (2.5 eV)
Visible light blue-green	500 nm	0.002 KeV (2 eV)
Visible red light	700 nm	0.0015 KeV (1.5 eV)

Until the gamma ray is not converted into visible light it has a quantum integrity. Or it collides with something and is detected, or it pass through undisturbed.

As an example we take a beam range of 32 Kev, when this gamma ray collides in a sensitive area and produces a flash of visible photons have the same energy as when he left. This though has passed through the air and other substances such as aluminum, plastic and crystal and although it has come a long way, for example by another galaxy up to ours, at the end will have exactly the same 32 KeV energy than when it is was created.

The energy of a photon range can not be "diminished" in any way, or it stops and then the gamma photon disappears converted into something else, or it continuous undisturbed on his way.

After converting the gamma photon in many photons of light, however, things change. The thousands of light photons that make up a single pulse are still to come to the photo-cathode of the photomultiplier tube and many of them fall by the wayside.

The chances of getting lost are many, some of the photons collides with a particle of dirt, others are born with a direction that leads them to bounce several times on the walls of glass and disappear before reaching their destination, others can come away from the tube and PMT lost during the passage through the crystal.

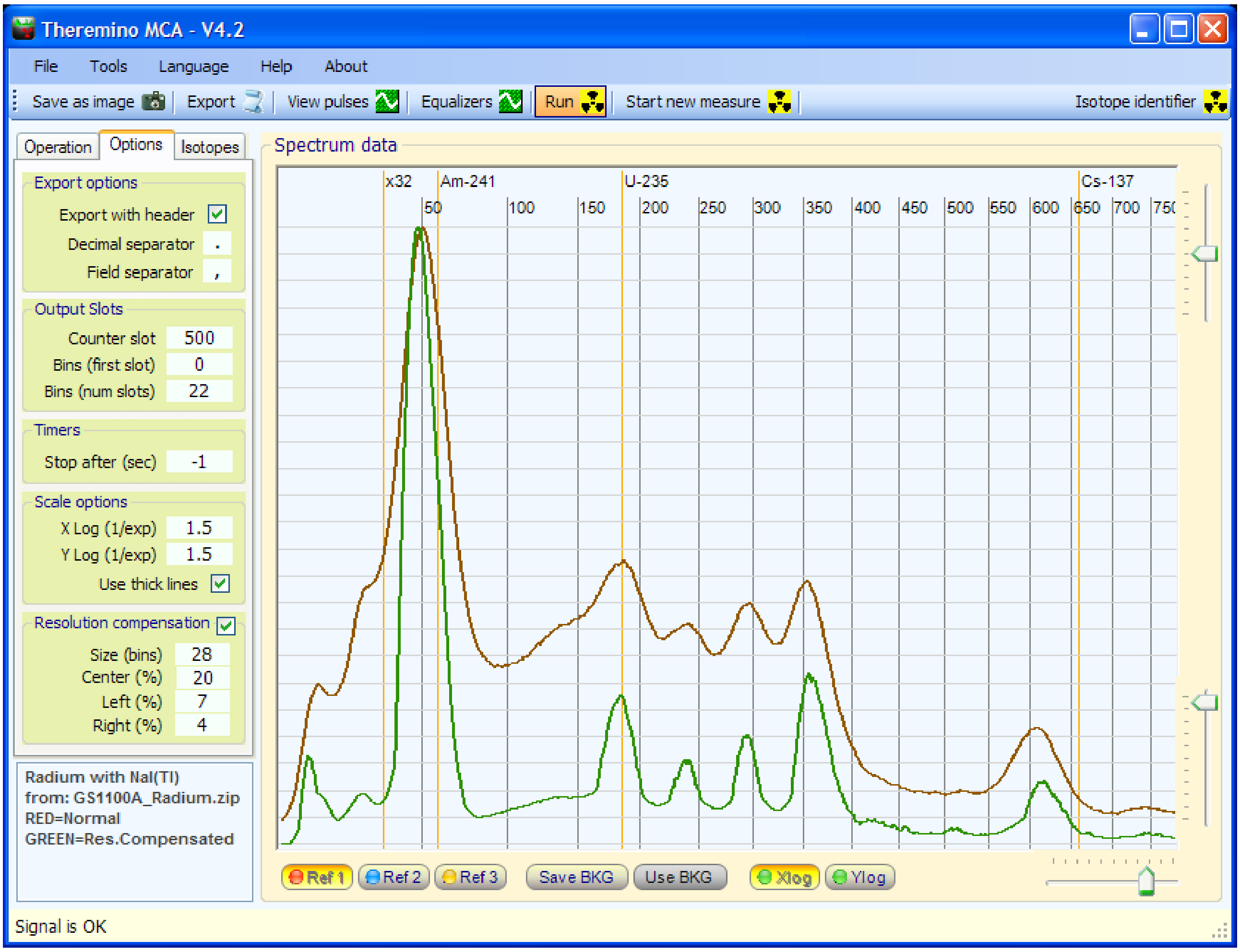
In some cases, fortunately quite few compared to the total of the 1000 original photons, there are only 900, 500 only rarely, and in some rare cases even much less. This produces a widening of the lines to the left. The enlargement to the right is smaller because, if they are parties in a thousand, more than one thousand original can not arrive.

Compensatory enlargement of the lines

The crystal scintillators produce a broadening of the lines, their resolution is still too low. The BGO crystals have a width from 12% (FWHM), the crystals NaI(Tl), much more expensive, arrive to 6%.

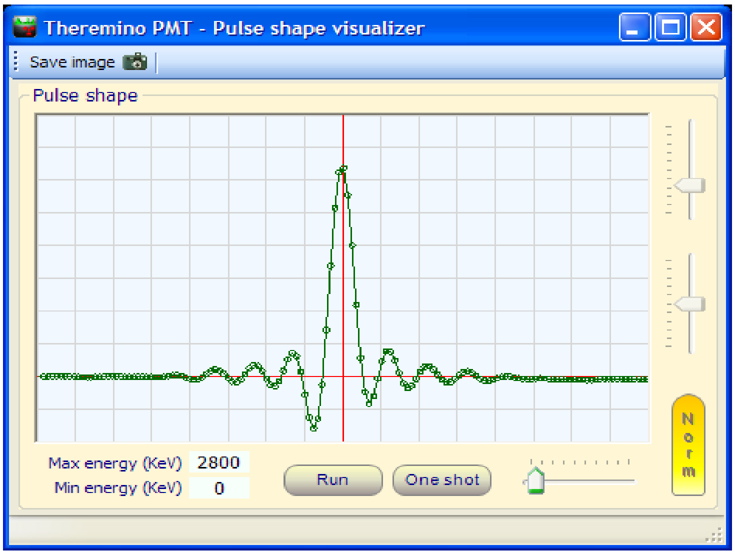
A compensation algorithm of resolution works in a similar way to the algorithms of increase of the definition of the images and can earn some percentage point and can easily lead the BGO below 10% and the NaI(Tl) below 5%

Even small improvements in resolution have a great effect on the visibility of the lines of isotopes and lowers the carpet of noise, making the lines appear smaller, which would otherwise be invisible.



Here we see a spectrum of the radio with a crystal NaI(Tl). Without compensation of the crystal resolution (red) and with the compensation that has significantly lowered the carpet of noise (in green)

The baseline (Baseline Restoring)

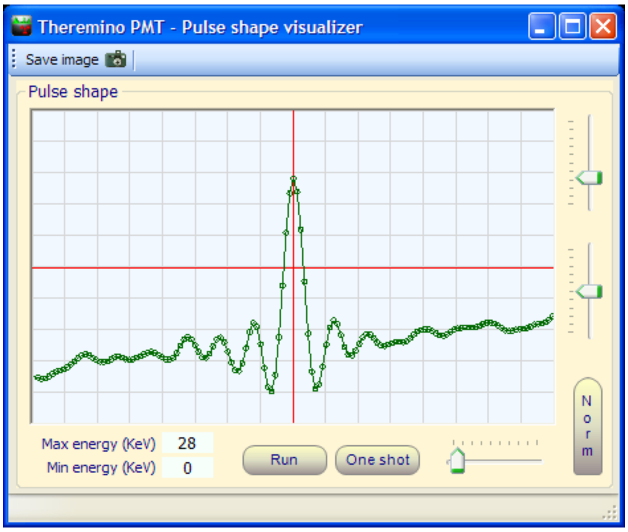


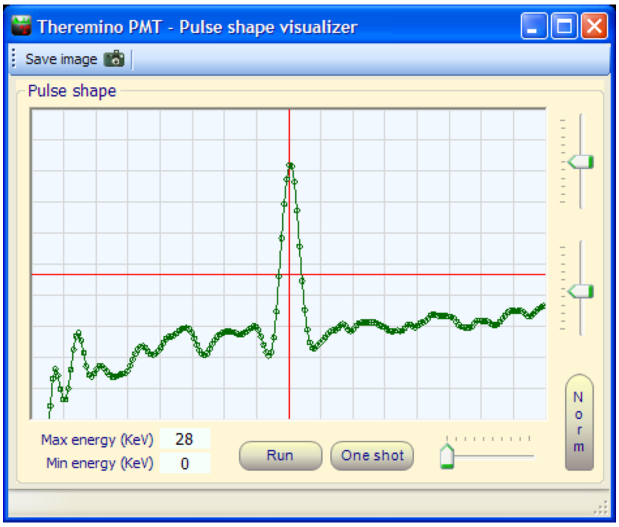
Would love to always have well-aligned pulse on the zero line, as in this picture, but few hardware can keep all the impulses in their place.

To have the baseline always stops the entire signal chain should work completely in continuous, without decoupling capacitors. It is not only the sound card but also of the decoupling capacitor of high voltage.

On the other hand a coupling totally in continuous cause many problems, including the displacement of the base line from zero as the temperature changes.

That means that we have to live with a baseline unstable as in the next two images.





The "BaseLine" tends to be lower when there are many impulses and to get up in the pauses between pulses.

As a result the pulses are measured with lower energy of the real (only the part that rises above the red line) and this causes a widening of the lines and an increase in the carpet of noise on the left side of the rows.

The bipolar pulses

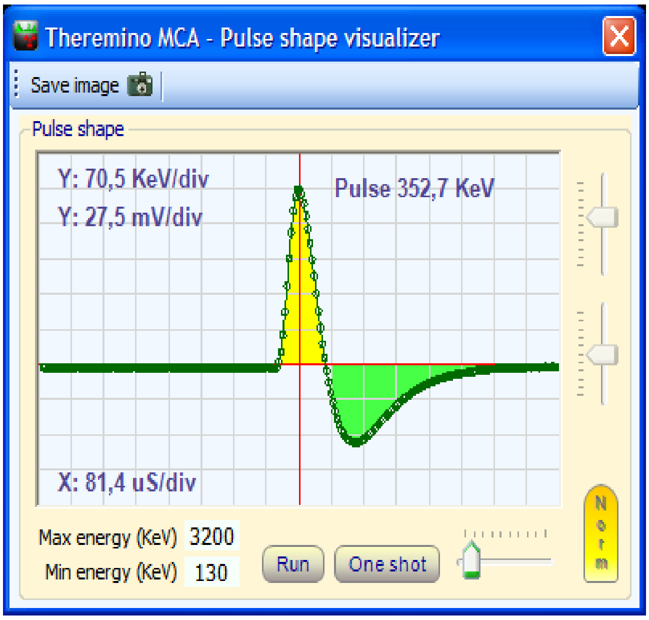
To minimize the displacements of the base line also with input circuits AC coupled, is good to use "bipolar pulses"

The bipolar pulses are characterized by a zone of negative signal that follows the main pulse positive.

The first part (positive) and the second part (negative) **must have the same area.**

This type of signal is obtained starting from a positive signal "without undershoot" and adding a high-pass filter with 6dB per octave, with cut-off frequency of about 5 KHz.

The high-pass filter has also the beneficial effect of eliminating the noise in the lower part of the spectrum.



***Why the PmtAdapter** carefully produce a signal with no undershoot and then we degrade it in this way?*

***Because only starting with a signal "without undershoot"** we are able to produce a perfectly balanced bipolar pulse, with the positive and negative areas perfectly equal to each other, that eliminate the slippages of the base line.*

A method of Baseline Restoring

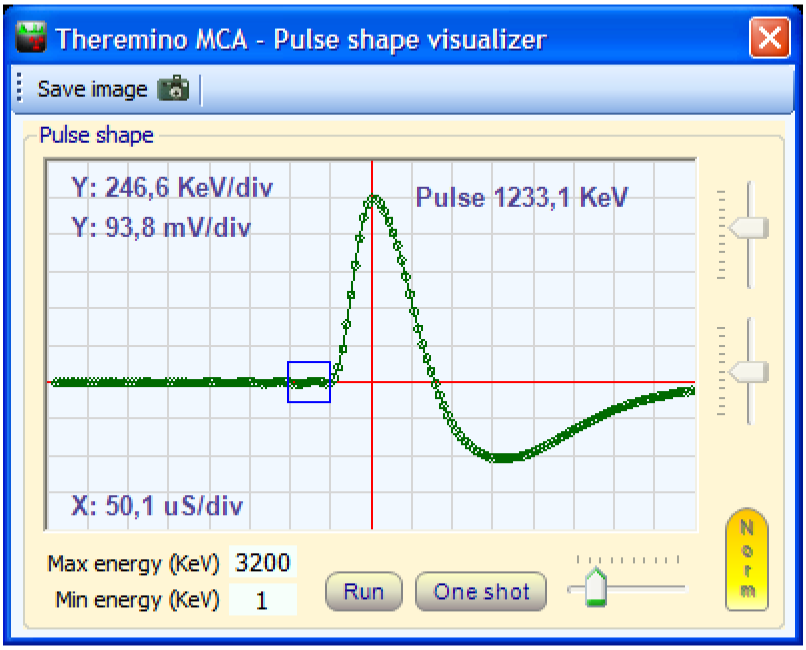
Since the correct "baseline" in hardware is difficult and expensive it is good that the software can make this correction.

In addition, also the best signal filters do not produce a very stable baseline and a "final correction" is always helpful.

The best point to measure the voltage of zero baseline is the area immediately prior to the pulse.

ThereminoMCA does the mean of all samples for a determinate time (defined by "Size"), which precedes the center of the pulse of a time (defined by the "Position")

The average of these values is used as a "best estimate" of the zero level.



In this image, the blue rectangle indicates the area where sampling is carried out.

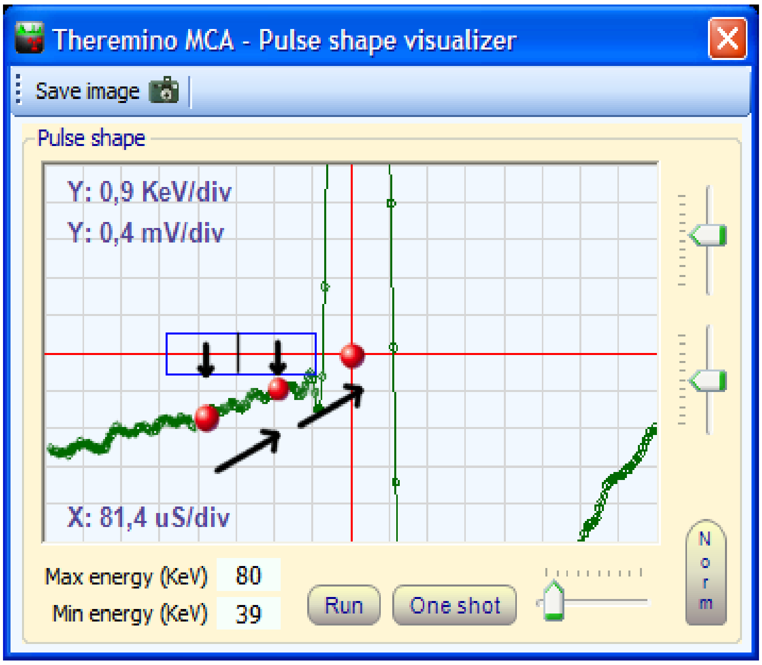
Taking into account that each square is worth about 50uS we see that the sampling has been set to a width of 50uS and a distance from the center of the pulse also of 50uS

The Baseline Test

The method to integrate the area immediately preceding the pulse provides good results but has little defects, which can be improved.

To improve the recognition accuracy of the voltage "Baseline" you should increase the size of the sample, so as to get a good average of the noise and "ringing" but, unfortunately, enlarging the area its center moves away from 'pulse and this causes inaccuracies when the base line is not horizontal.

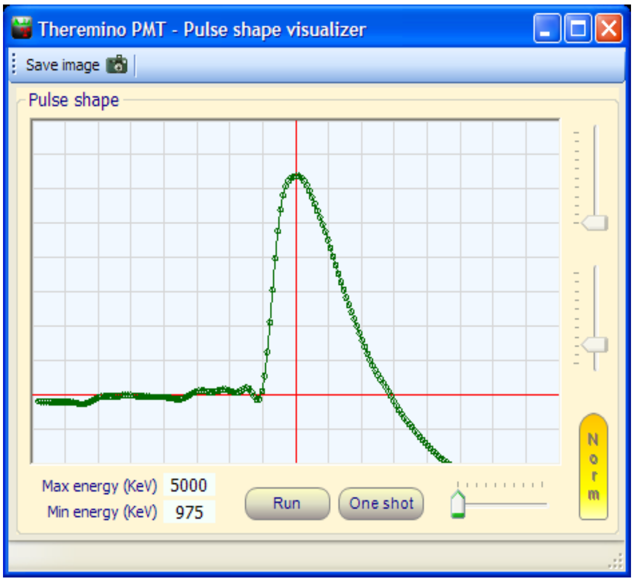
In order to increase the size of the sample area, the area is divided into two separate areas and two separate averages are measured. The two measured values allow to calculate the slope of the baseline and to accurately correct the position of the zero pulse.

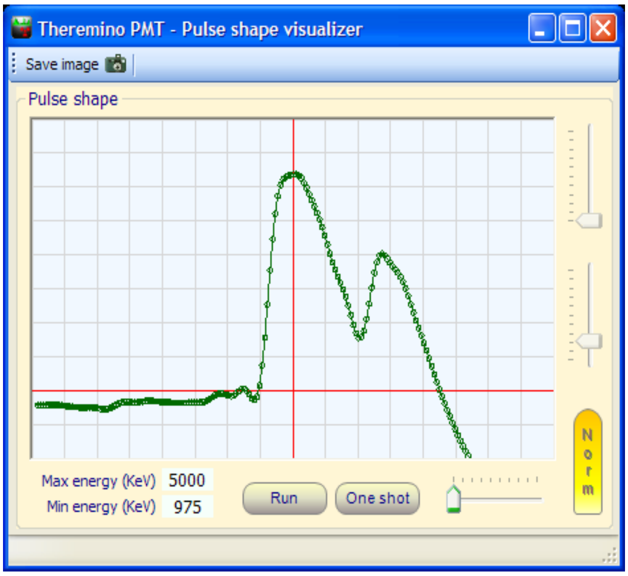


The two averages (red dots on the left) are used to calculate the position of the zero in the center of the pulse (third red dot)

The new "Baseline Test" implemented in version 4 of ThereminoMCA, is a significant improvement compared to baseline Restoring the version 3 and also helps to eliminate the pulses too deformed with the settings "Max slope" and "Max noise"

The pulses overlap (pileup)





Picture 1 - pulse without "PileUp"

Picture 2 - Pulse with "PileUp"

Here is a good example of "pileup" the second pulse arrives when the first one is not finished yet.

The second pulse relies on the first, is higher than it should, and ends in a wrong bin.

Given that the relative position of the two pulses is randomly even the bin of the destination is, with the result of raising the carpet of noise in a uniform manner. If PileUp are very frequent noise rises to the point of masking the lines useful.

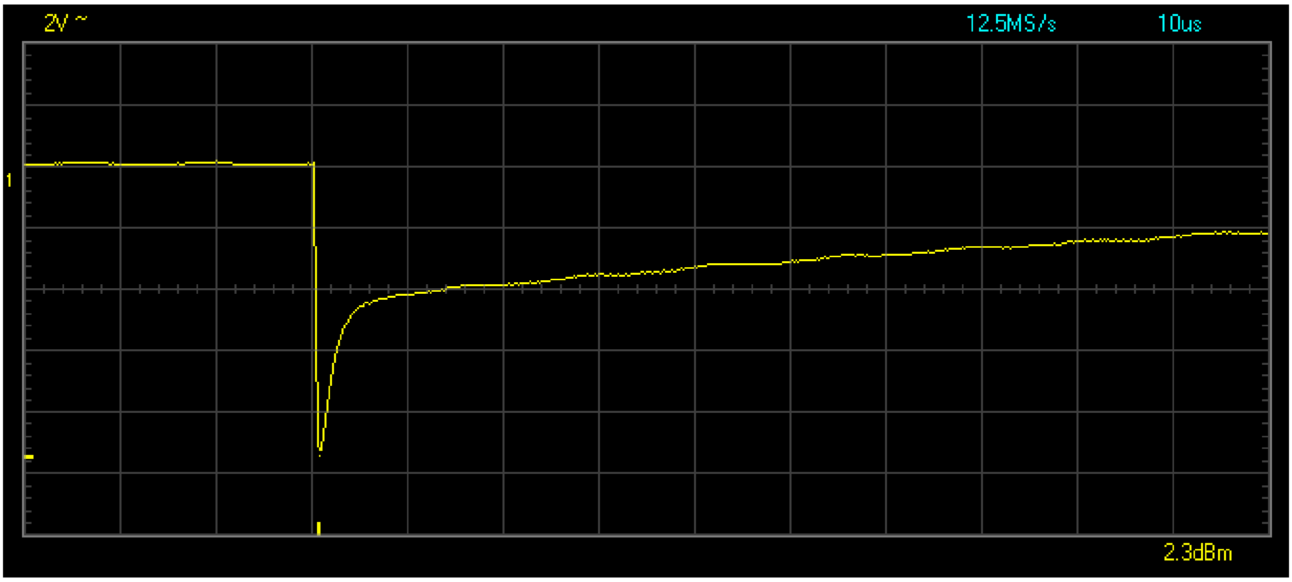
Both the method of recognition of the shape of the pulses "Shape Recognition" (used by the PRA), both the method "behavioral" (used by ThereminoMCA) fail to eliminate the defects caused by the PileUp however, as already seen in the previous pages, also in this case The behavioral method is better, here is the behavior of the two methods:

- The "Shape Recognition" recognizes that the shape is wrong and discard both pulses.

- The ThereminoMCA uses normally the first pulse and discards only the second.

The width of the pulses

The pulses coming from the PMT tube are rectangular and very narrow (less than a uS) but with just a minimum of capacity (for example 50 inches of shielded cable) they lengthen to about 3 uS.

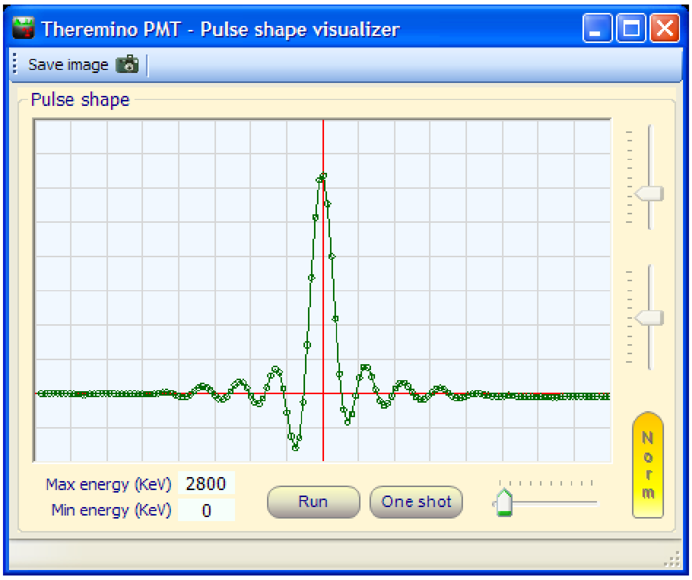


Here we see a pulse measured just after the decoupling capacitor high voltage. The tension on the PMT is 900 Volts and the photon that generated it was from about 1 MeV. Here you do not see very well but the point is high almost 10 volts and is largely about 3US.

This pulse contains the maximum of its energy around 300 KHz that are more than ten times the bandwidth of the sound cards (always 20 kHz also with 192 kHz sampling cards)

If we send a similar pulse to the soundcard it will be almost completely eliminated by the input filter and the signal to noise ratio will decrease a lot.

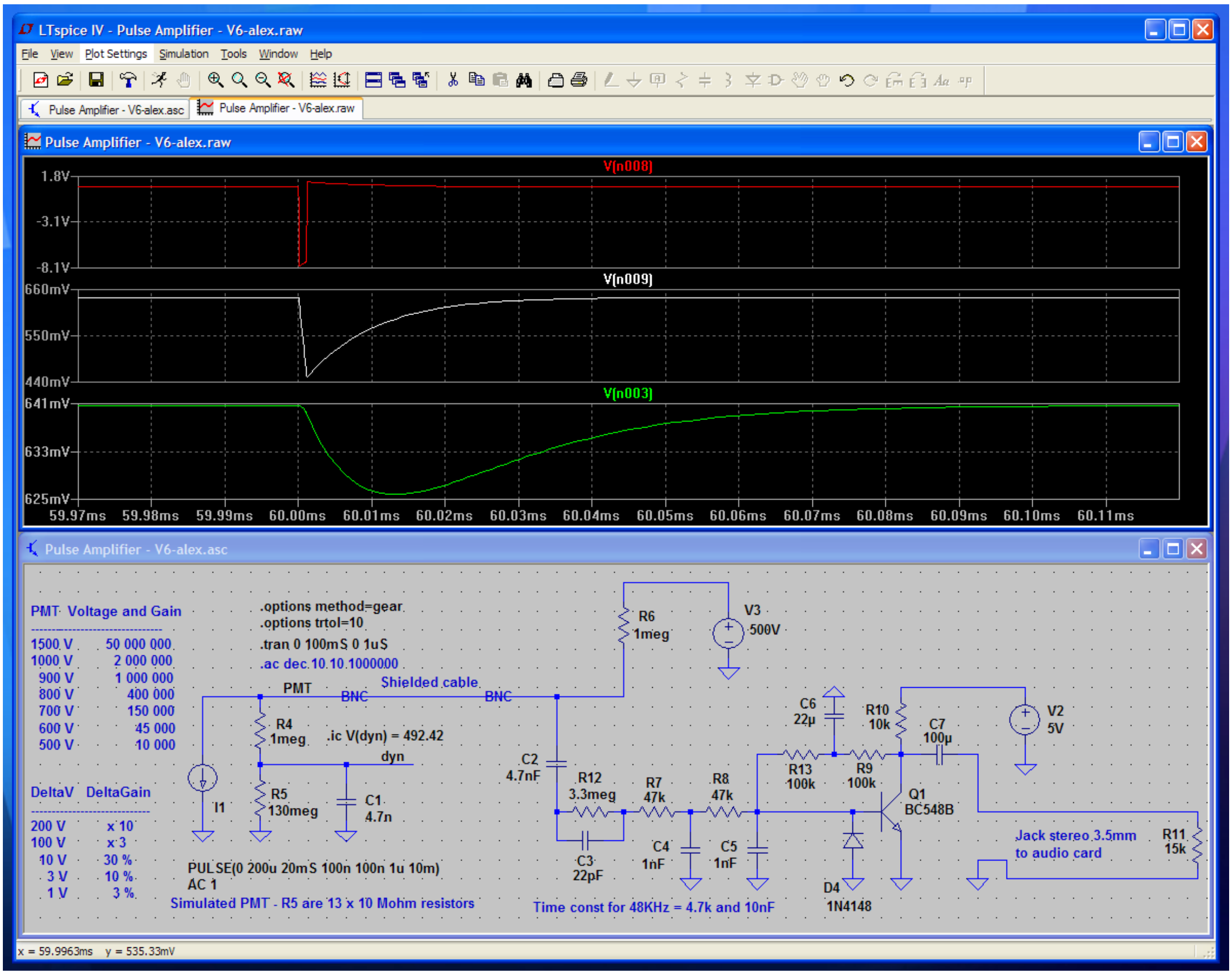
A second effect of a so rapid pulse is the production of a considerable "ringing" in the filter "anti-aliasing" of the sound card. This image shows a ringing for almost 25% of the pulse.



The filters sound cards are adequate for normal audio signals that never contain components at frequencies above 20 or 30 KHz and are high about 1 Volt, but they go to the ball, when you shots 10 Volt to 300KHz to them.

Another defect of the narrow pulses is to have a tip as a needle, so that if sampling did not happen exactly at the tip, the measured value changes greatly, resulting in enlargement of the rows.

The, signal conditioning, hardware filters



This schematics is just an example and does not match the PmtAdapter latest versions for the final circuits, read the documentation PmtAdapter.

This simulation shows how the first cell of the filter broadens the signal without rounding its tip.

Only with two consecutive low-pass cells you get a rounded tip, which is what is often called "Gaussian pulse", for its resemblance to the well-known "Gaussian" curve, widely used in statistics.

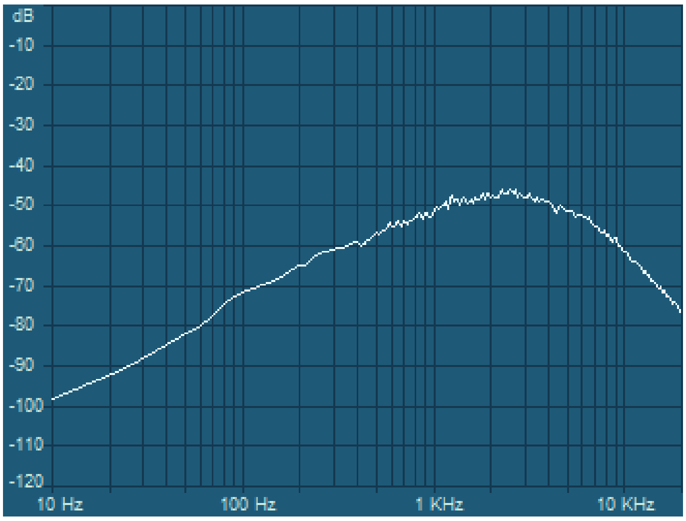
The bandwidth

Seen in terms of bandwidth the result of all filters is as follows:

- Maximum gain around 3 KHz

- Attenuation of 18 dB/octave over the 6 KHz that eliminates the high frequency noise, slows down the rising edge and reduces to a minimum the "ringing" generated from the sound card.

- Attenuation of 6 dB per octave below 3 KHz which eliminates low-frequency noise and reduces (by 35 dB!) Any hum at 50 or 60 Hz.



This image represents the pulse energy at various frequencies and has been produced with a sample of cesium to have pulses per second (over 600) and with the DAA set for integrating over time the graph of frequency response (parameter "speed" almost minimum)

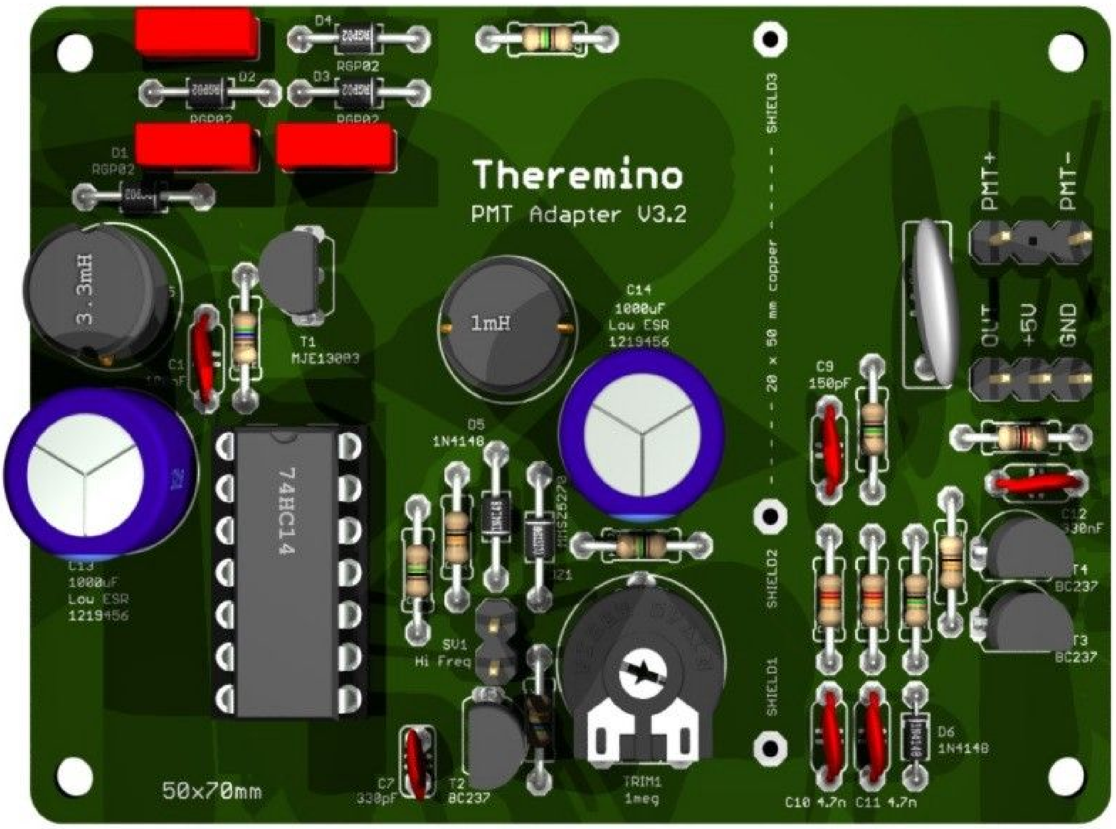
The noise produced from the hi voltage supply

The photo-multiplier tube has a very low consumption and steady, just feed it through two cells from 1 Mega ohm + 47 nF capacitor and all the noise disappears.

If not disappears then passes through the air to the small capacity that is among the components of the power supply and those of the circuit of the audio signal, in this case it must separate the two parts with metal screens in aluminum or copper.

If still the noise of the power supply does not go away may be due to a "ground loop" that too many masses and placed evil. In such cases it may also help to add a very large electrolytic (1000 uF - low ESR) between the positive five volts and ground.

The Theremino_PmtAdapter



This power supply (and signal conditioner), solves all the problems of the previous pages, removes the ringing and produces a signal with very low noise.

Unlike many, non-stabilized, commercial power supplies, which require ten minutes of preheating, the Theremino PmtAdapter contains a feedback circuit, which keeps the stable voltage, even in the presence of strong variations of temperature. In this way the calibration remains accurate over time and the rows of the isotopes do not move and do not widen.