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Calibration of Charge Amplifier and Discriminator Circuits used in the JRC Drum Monitor, Slab counter and BBNCC devices

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Varasano G.,
Bogucarska T.
Pedersen B.,

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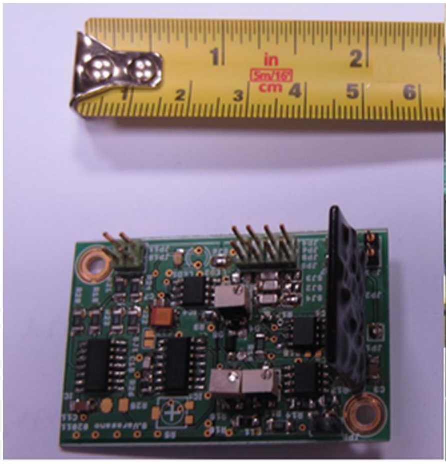

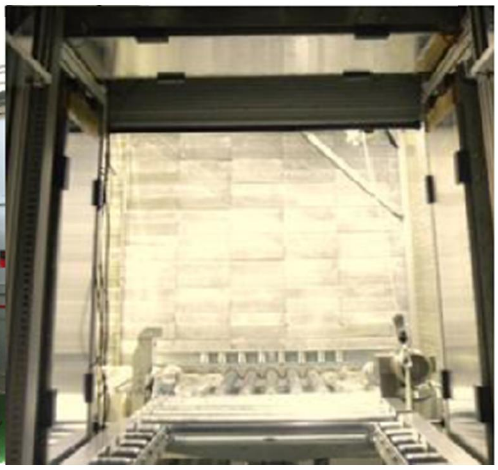

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Contents

Abstract

An analogue charge amplifier and digital pulse discriminator circuit has been designed and implemented at the JRC-GII.7 applicable in the JRC Drum monitor and a novel Slab Counter device, manufactured in 2015.

This technical note provides the details suitable for proper operation and an optimal setup of the charge amplifier and pulse discrimination circuitry.

1 Introduction

JRC Drum Monitor and Slab Counter devices are safeguards counter used by Euratom inspectors for physical verification in European nuclear fuel cycle facilities.

The JRC Drum Monitor is a passive neutron counter intended for safeguards verification of 55-gallon drums in European nuclear fuel cycle facilities. This instrument incorporates 148 ^{3}He tubes arranged in a 4∏ geometry. The ^{3}He tubes are spread among ten vertical and four horizontal modules. Each module contains the electronic circuitry, consisting of a charge sensitive amplifier, a pole/zero shaper and a digital discriminator circuit, which produces a digital TTL signal for each neutron detected.

As a first implementation it was used an inexpensive commercial charge sensitive amplifier that in a near future will be replaced by a complete custom design. This report describes the new design of electronic components of those instruments. In addition it includes a calibration procedure of the charge amplifier and discriminator circuits.

The simple 1st order Pole-Zero (RC-CR) pulse shaper also considered to be a good choice, as our devices are meant to be used at low count rates. A limitation in our circuit is due to a compromise we must accept in our discrimination circuitry between dead time and improved noise margin to reduce multiple pulses. Multiple pulses cannot be eliminated by design in principle but in our circuitry the chance for them to happen is very low, as it will be explained later on.

2 Neutron coincidence counter layout

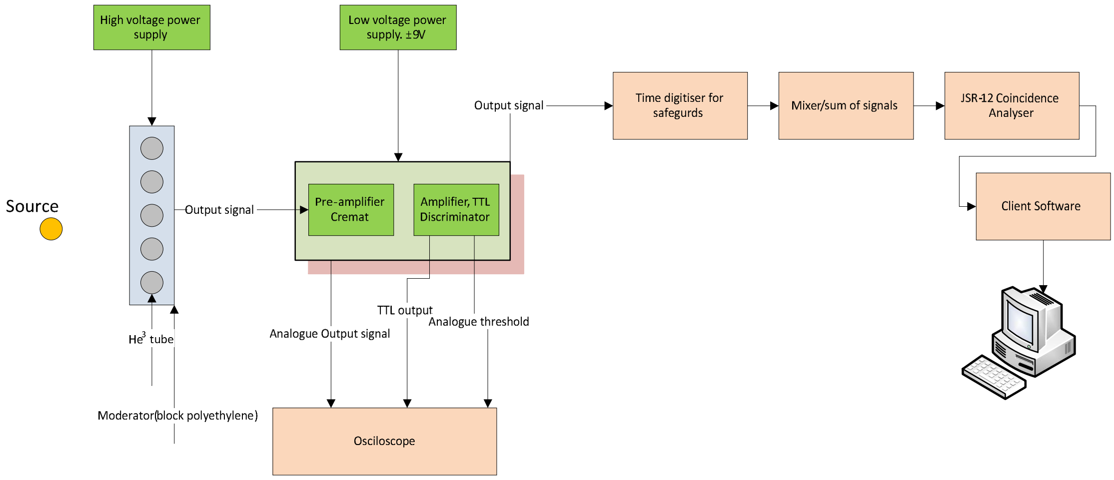
The JRC Drum monitor incorporates 148 ^{3}He tubes arranged in a 4Π geometry (Figure 1). It is designed to maximize counting efficiency for conditioned waste drums of low Pu content. Minimization of structural components in the drum cavity was undertaken to lessen background from cosmic ray-induced spallation neutrons in high Z materials. The detection system is optimized for standard neutron multiplicity counting to yield the mass of plutonium through the absolute determination of the spontaneous fission rate of the waste drum.

Figure 1. JRC drum monitor ^{3}He tube layout

The ^{3}He tubes are spread among ten vertical and four horizontal modules, totaling 2x10x5=100 tubes + 2x4x6=48 tubes. The vertical slabs are numbered in a clockwise direction. Six of them 7, 8, 9, 10, 11, 12 are built in and constructs the walls of the measurement cavity. Other four vertical slabs, contained in the openings doors have numbers 5,6 (left door) and 13,14 (right door). Remaining slabs with reference numbers 1 and 2 are placed at the bottom and 3,4 at the top of measurement cavity. Each slab, containing two sections, each with five or six ^{3}He tubes , is further subdivided into two parallel analogue amplifier/discriminator circuits, contained in a brass box where the gas filled proportional counter tubes are screwed (Figure 1). The box, divided into two compartments, has a bottom part containing the wiring for the positive high voltage potential, to be applied to the anode of the gas detectors; the upper part of the box contains the electronic circuitry, consisting of a charge sensitive amplifier, a pole/zero shaper and a digital discriminator circuit, which produces a digital TTL signal for each neutron detected.

Thus a total of 28 digital signal outputs are available; these can be collected and distributed using 50 ohm coaxial cables ending with standard BNC connectors. These signals can be subsequently fed into a field-programmable gate array (FPGA) based digital signal mixer unit producing a single signal pulse train [10]. Canberra JSR-12, JSR-14 or JSR-15 shift register can process the pulse train, and all neutron multiplicity analysis is performed by standard client software ([1]). In addition novel Time Digitizers for Safeguards instrumentation [9] (two models TDS8 and TDS32 are available featuring 8 and 32 input channels) have also been developed at the JRC-GII.7 for the purpose of implementing PC controlled versatile programmable devices, downloading VHDL codes into FPGA logic through an USB link, to implement in software shift-registers algorithms and generic post-processing routines to find out and remove noise artifacts form the pulse train to be analyzed ([2].).

Figure 2. Electronic Circuit



1

2

3 Pulse signal formation

A charge amplifier is normally used to produce a voltage signal proportional to the energy of a radiation event. In our case, the charge collected from the ionization of ^{3}He gas in proportional counter due a neutron interaction event.

In our measurements we are mainly interested to count such events and perform a further multiplicity analysis of the frequency distribution of radiation events[5,6,7,8]. Even not being so much interested in getting the full-energy peak of the signal, particular care must however be taken to lower the overall electric noise in the measurement chain. The main sources of noise comprise the gas tube, the charge amplifier, the Pole/Zero shaper network and the discrimination circuit following the analogue stage producing a digital TTL signal to be propagated through a 50 ohm line driver to measurement devices, possibly avoiding the formation of multiple wrong pulses. The noise might compromise the measurement and its further analysis.

> As a general recommendation is useful to put a filter on the High voltage supply line (see the details in chapter 4 - Circuit Description).

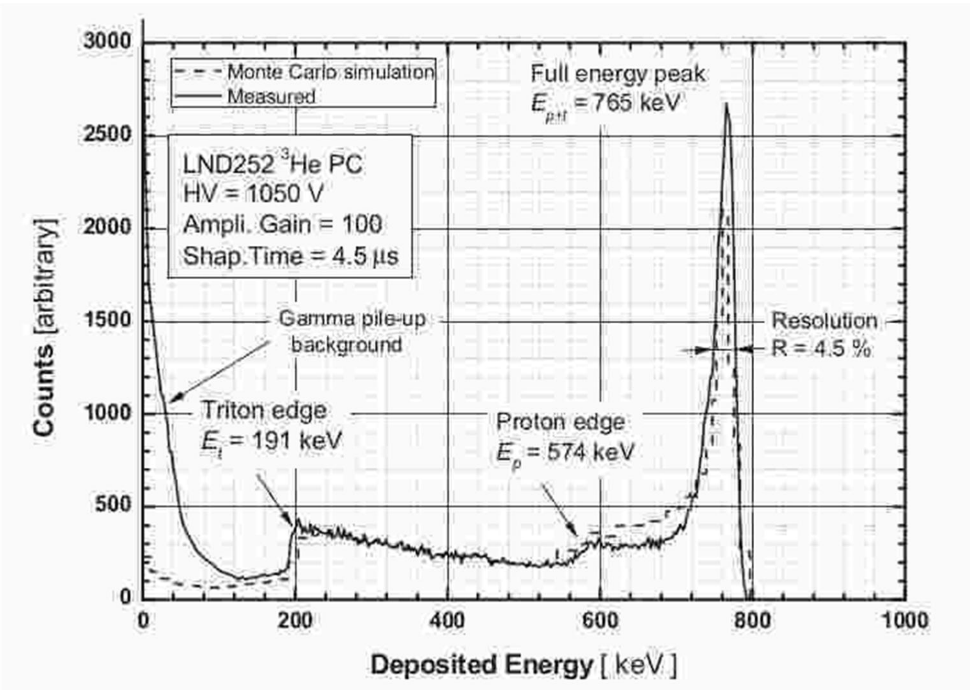
The ^{3}He gas-filled proportional counter is a long-established and widely used sensor in instrumentation for thermal neutron detection. Helium-3 proportional counters utilize the ^{3}He (n,p) ^{3}H reaction for the detection of thermal neutrons.

$$^{3}He + n^{1} \text{ (thermal) } \rightarrow {}^{1}H + {}^{3}H + Q \text{ (reaction energy) } \quad \text{where } Q = 765 \text{ Kev}$$

The energy of the reaction is carried away as kinetic energy of the daughter products (proton and triton), which move in opposite directions.

A figure the x-axis is energy and the y-axis is the count rate, is introduced below in Figure 3.

Figure 3 ^{3}He proportional counter spectrum



Source: D. Mazed , S. Mameri , R. Ciolini, Design parameters and technology optimization of 3He-filled proportional counters for thermal neutron detection and spectrometry applications.

The dominant feature is the full-deposition peak at 765 Kev. The two edges in the spectrum near 200 Kev and 600 Kev are related to partial energy deposition in the gas when either the proton or the triton interacts in the wall, so only one particle charge is collected in the output signal. As an output of the charge amplifier we therefore expect a variable voltage signal proportional to the different collected charge.

Unipolar or bipolar shapers can be used. The advantage of bipolar shapers is more evident at high count rates, due to their intrinsic baseline recovery capability. In our case we used an unipolar shaper because a voltage threshold between signals due to radiation events and what is collectively named electronic noise can be easily evaluated and set just below the voltage corresponding to the minimum energy collected by triton as it shown in Figure 3.

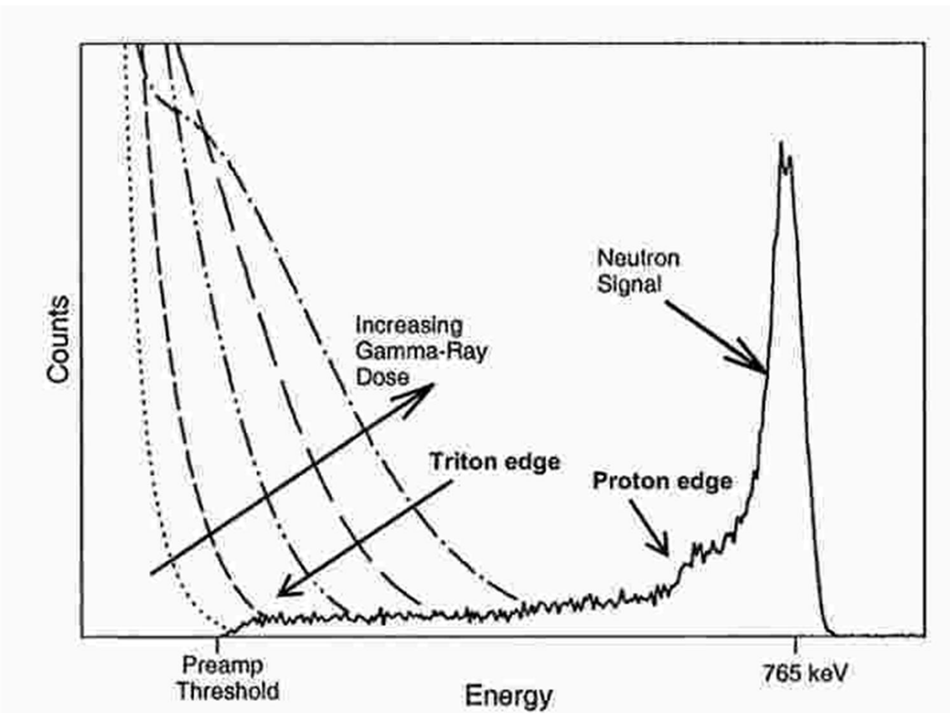
The dynamics of the analogue signal in our circuit is wide enough to have an ample noise margin in order to detect possibly all the events really due to neutrons to be measured.

The wall-effect, the two edges shown in the figure 3, arises because the energies of the proton and triton daughter products of the reaction have discrete energy levels (respectively at 574 keV and at 191 keV). When these products collide with the wall of the tube, the energy is dissipated and spread in the energy spectrum. This effect must be reduced when manufacturing the tube.

A valley is visible in the region below 200 keV, where a not so sensible amount of pulses is detected. Here is the region where electronic noise of the amplifier or a contribution from gamma rays comes into play, so a voltage threshold must be established in this valley, just below the triton energy introducing a discrimination voltage in a convenient way so as to avoid rare but unwanted pulses triggered by the noise of the electronics or by unavoidable random processes.

In a mixed neutron-gamma field, however, the gamma rays interact in the ^{3}He proportional counter by producing an avalanche of secondary electrons from the inner wall of the cathode tube. As the gamma ray dose increases, the avalanches begin to pile up.

Figure 4. Pulse height distribution in a ^{3}He tube

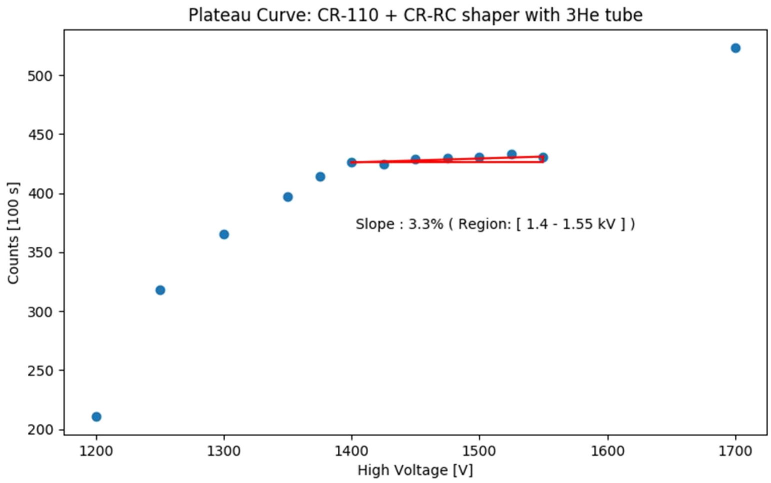


Source: D. Mazed , S. Mameri , R. Ciolini, *Design parameters and technology optimization of ^{3}He-filled proportional counters for thermal neutron detection and spectrometry applications.*

The pulses which are produced are large enough to exceed the charge amplifier energy discrimination threshold for neutron events. In this case gamma pulses can be erroneously counted as neutrons. The effect is described in figure 4.

A so-called 'plateau' curve should be preliminary determined in order to setup the proper positive high voltage by applying a proper electric field between the anode and the cathode of the gas-filled tube. Plateau curve, CR-110 +RC-CR shaper with ^{3}He tube is presented in Figure 5.

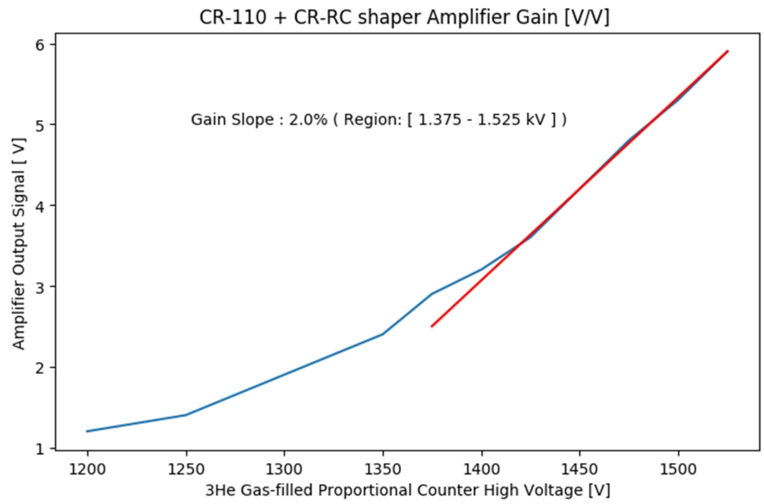
Figure 5. Plateau curve, CR-110 +RC-CR shaper with ^{3}He tube



Experimentally determined values for our configuration of the JRC Drum monitor's electronics are:

- The high voltage is 1100 V on a set of gas-filled tubes, in particular the smaller length ones contained in the opening's doors (for slabs 5,6 installed in left door and the slabs 13,14 in the right door).
- For all other tubes, the high voltage is determined equal to 1400 V.
- The gain of the analogue circuit set to give 3V voltage output corresponding to a signal full energy peak.
- A "radiation" threshold set in the range 500-700 mV. It is set on a two-fold adjustment acting upon two trimmers for setting both the energy threshold and a superimposed noise margin to avoid the formation of multiple pulses as explained later.
- Qualitative plots are shown [figure5,6], just to provide a confirmation using a ^{252}Cf source that values where properly set.

Figure 6. CR-110 +RC-CR shaper amplifier gain



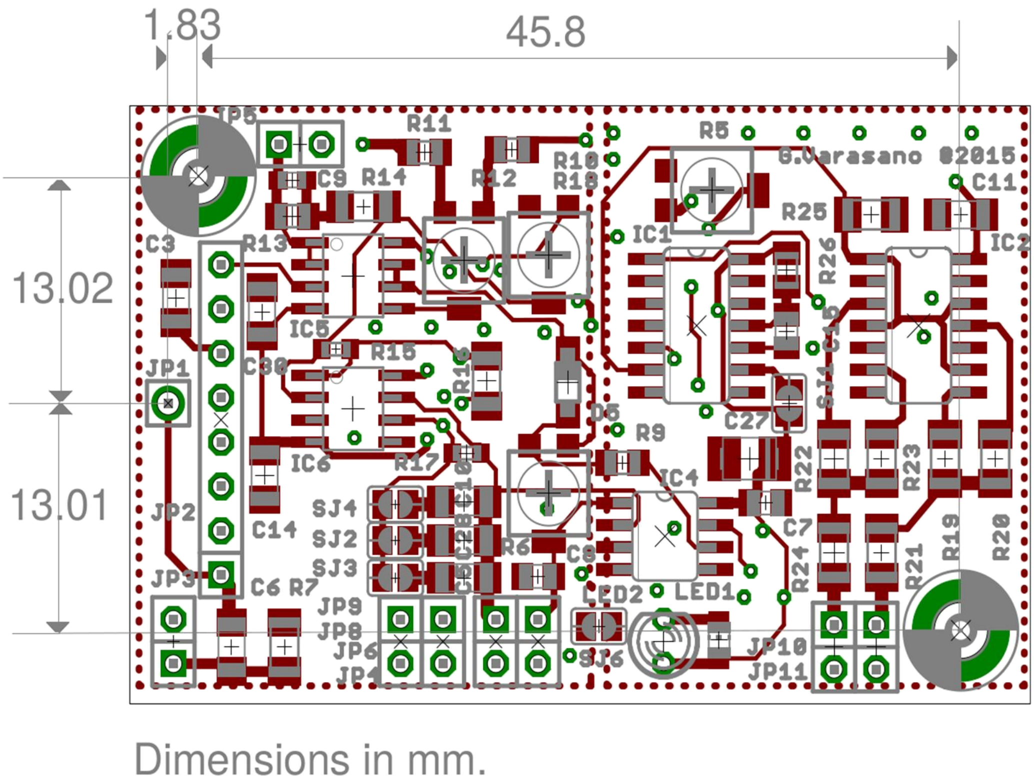
4 Circuit Description

The circuit consists in a charge sensitive amplifier, model CR100 from CREMAT Inc. (Annex 1), followed by a RC-CR Pole-Zero compensation network in order to provide a pulse, whose maximum amplitude, reached at the peaking time. The pulse is proportional to the charge collected from a multiplication of an ion-pairs production in a proportional counter such as a ^{3}He gas filled proportional counter.

Different shaping times (500 ns, 1us, 2us) can be selected by soldering drops of stain (jumpers) on the printed circuit board (PCB).

Schematics and design of the Pole/Zero network and the digital output pulse discriminator circuit and driver can be found in the Annex.

Figure 7. The pinout of the circuit and the layout of the trimmers



Here the figure 7 shows the pinouts of the circuit and the layout of the trimmers used for adjusting the radiation signal threshold (R12), the gain (R18) and the superimposed noise margin level (R6). An additional trimmer (R5) is not mounted.

The input of the charge preamplifier is connected to the high voltage anodes of several ^{3}He tubes by an external high pass decoupling network (C=10nF, R >= 1-1.2 MΩ). The same concept is used in the JRC drum monitor and the slab counter devices.

Usage of good manufacturing practice and experimental technique lets the user to have properly isolated screwed tubes by applying high voltage to the anodes, connected in parallel. The high voltage section is isolated from the low voltage section by an additional brass plate.

The manufacturing technique of brass boxes lets to properly isolate and screen the high voltage section from the low voltage upper part of the box, where the charge amplifier/discriminator circuit is housed.

We used a low-pass filter at the output of the Drum Monitor's high voltage supplies, both for the 1400 V and 1100 V rails. This filter proved to be effective to cancel out and lower the effects of several disturbances when we applied to our circuits an external high voltage coming out from the supply of some commercial shift registers. The periodic high frequency spikes, due to the saturation of power inductance used in DC-DC converters contained in the devices, were detected as radiation signal pulses. The filter simply consists of a cascade of 3 RC stages followed by a current limiting resistor. The values we used where R=1.5MΩ ad C=10nF (4KV) for the filter and R=24 MΩ as the additional resistor.

A JP1 Pin (OXELEY Inc.) is used to connect the charge amplifier input to the anode of the tubes. Due to the AC coupling no high voltage can be present to the input pin but only the front edge of the pulse is propagated.

JP5 is a test point where the exponential output of the CR-110 preamplifier, having a decay constant of 140 us, can be observed.

Due to the capacitor load of the cable of a distant oscilloscope, the final pulse output can be deformed, it can became more similar to a Gaussian pulse, due to the additional formation of a integration stage.

This is the reason why attaching a probe at this test point is just to provide a qualitative measurement to check what is coming out from the CREMAT preamplifier.

A test pin is provided to inject a charge in order to calibrate the gain of the amplifier, set thresholds and output a digital pulse.

JP3 pin header (a 10 pF capacitor and 50 Ω terminating resistor) is used as the test input.

A programmable pulse generator Agilent (Hewlett Packard) 33201 was used to generate a square waveform having 50 mVpp amplitude at the laboratory.

A 10:1 resistor divider (470 Ω in series to the test pin)) is used to further reduce the amplitude of the input signal to 5mV, provide an injection of 50fC charge. The Table 1 shows the PCB board the Header layout starting from left bottom side of the PCB board the Header layout (JP9,8,6,4).

Table 1. PCB board Headers Pinout (JP9,8,6,4)

JP9		**JP8**		**JP6**		**JP4**	
x	supply(-9V)	x	supply (+9V)	x	Analog Output	x	Threshold DC output
x	ground	x	ground	x	ground	x	ground

In the reference to Figure 10, the pins at the extreme bottom right of the circuits are the 50 Ω terminated lines to output the digital pulse as presented in the Table 2.

Table 2. PCB board Headers Pinout (JP10, 11)

JP10		**JP11**	
x	50 Ω TTL Pulse Output	x	50 Ω TTL Pulse Output
x	ground	x	ground

The pulse is split at the output for user's convenience. One output can be connected to a counting device such as a shift register or multiplicity counter, while at the same time the other output can be sent to a 50 Ω terminated oscilloscope input or a standard 10 MΩ high impedance probe. In the latter case reflections are expected to be observed. The high impedance is needed when observing the analogue pulse. By this way, the user doesn't set sometimes by mistake the input for digital signal to a 50 Ω termination.

The digital output pulse can be affected by cabling. This may lead to pick up noise from the environment and the effect is to superimpose this noise to the analogue pulse output.

A perfect rectangular shaped digital pulse having a width of 40 or 50 ns is expected to be seen at the digital output pins. (By mistake resistors with different values have been mounted on current prototype boards giving rise to shorter widths of 40 ns instead of the planned 50 ns). When the line is terminated to 50 Ω load, the standard 5V (4.5V) TTL output is reduced to a 2.5V (2.2V). pulse; this voltage level is , however, enough to trigger a CMOS or LVTLL levels or a standard TLL level available as the input of commercial counting devices.

N.B. Some commercial Shift register devices' BNC input connectors are not 50Ω terminated, but have input impedance of the order of 400 Ω or 1KΩ. In our case the reflection amplitudes are not high enough to create problems.

As soon as a pulse is generated on the output pin, the led on the PCB blinks. The time-constant constant of the mono-stable circuit driving the led has been chosen to be of the order of 5 ms. These "blinks" are observable due to the image persistence of the eye and brain having the proper value to see sequences of low rate pulses. If the pulses arrival rate is higher than 20/s the flashing light of the leds becomes a steady light.

The setup procedure depends at least on three different and quite independent trimmers.

The trimmers used for adjustment are:

- R12 - Signal Discrimination Threshold and Trigger level
- R18 - Pole/Zero network Gain
- R6 - Noise Margin superimposed level

4.1 Instrumentation for the calibration of amplifier circuits

The required instrumentation for the calibration of amplifier circuits is listed below:

- HP34401 digital multi meter.
- HP33201 programmable waveform generator, with a 50 ohm coaxial cable ending with a 10:1 resistor network and 2.54 inch header.
- TEKTRONIK 2/4 channels 100 Mhz Bandwidth Digital Oscilloscope.
- a -9V and +9 V power supply (the one at the top level). the wires are then terminated in two separate black coaxial cables, having a white stripe for the negative supply terminals and two white stripes for the positive supply terminals. Both cables end with 2.54 mm headers where the ground pin is clearly evident.

The procedure suggests using 2 or 4 channels oscilloscopes, available at the laboratory. Coaxial cables, terminated by 2.54 mm header, were manufactured to be used with the oscilloscope.

One channel must be linked to the digital pulse output. The threshold of the scope must be set to capture a raising positive pulse with a maximum amplitude 2.5 V signal (i.e. 1.2 DC voltage). This output should be DC coupled.

The other cable must be linked to the analogue voltage output (AC coupled).

As already mentioned it is not easy to see a proper blinking of the led at the beginning, due to the several adjustments to be performed. Therefore, the Arbitrary Waveform Generator (AWG) is setup in order to give a squared waveform with a 10 Hz period. It is easy using such a slow frequency to see if the amplifier works properly.

4.2 A DC voltage threshold

A DC voltage threshold, applied to the reference pin of the comparator, is used to discriminate between voltage pulses corresponding to gamma radiation and noise or neutron radiation.

Due to the characteristic response of a ^{3}He proportional counter a discriminating valley is expected between neutron and gamma energies (see figure 3). Using only a test generator we cannot see this separation.

By acting on the top leftmost trigger and putting the scope probe of the JP4 output pin shown in Figure 7, the technician may see that adjustments of the trimmer the DC voltage can range from negative to positive values (i.e. normally in the range -3 V to 3V).

A negative range is needed because the output of the charge sensitive amplifier CR100 can exhibit a negative DC offset when doing the final setup procedure. It is important to understand that a digital TTL pulse is output if and only if the output signal goes over a predefined threshold. This setup point can be reached by acting on the gain and then on the DC threshold regulation. When a threshold/gain setup point has been found, in case the user observes multiple pulses, an additional adjustment must be performed using the trimmer, at the bottom of the board, in order to superimpose a positive noise margin to the reached threshold.

This margin obtained with a parallel combination of a trimmer and a diode in the comparator's hysteresis loop path ranges from 0 to 0.7 V.

The real meaning and utility of this further regulation is best understood when performing the final procedure. An idea of a further improvement could be to use a series of N Schottky diodes instead of a standard diode (only 0 to 0.2V * N noise margin but a faster reverse recovery time).

Pulse discrimination is definitely an art. Additional circuitry or techniques could have been used. Here the aim was to avoid as most as possible the occurrences of multiple pulses introducing the least possible additional updating dead time. Here the dead time inevitably introduced is dependent only on the pulse output level. The shaping time is in the order of 500 ns for smaller signals, whose noise contribution must be minimized but the pulse has variable width according to the reached amplitude height.

The time (time interval of the window) that the comparator is unable to fire again has not the nature of a fixed duration dead-time such as those introduced by a mono-stable circuit following the comparator. Here the comparator doesn't fire again till the signal has not reached the lower threshold, so a window, yellow trace visible on the scope’s traces, is introduced as it shown in Figure 12. In a mono-stable controlled comparator's circuitry, the comparator fires just once and the dead-time has a fixed duration.

A better discrimination circuit could be proposed in a future, were the electronics’ induced dead time should virtually be eliminated.

5 Calibration procedures

A setup procedure is introduced to be eventually performed on circuits manufactured by third parties or when manufacturing additional spare parts to be used for repairing failing or poorly behaving and noisy units in example.

Two different and mandatory procedures must be performed:

1) An initialisation procedure when manufacturing the circuit board.
2) A setup procedure when using the circuitry in-field.

The first procedure is to be applied when manufacturing circuits. The proposed setup is quite deterministic because all produced units must behave the same. The aim of the preliminary coarse adjustments is just to verify that all parts needing an adjustment (i.e. trimmers) are working as expected.

At the end of the tests, the trimmer setting the gain of the amplifier can be adjusted in order to measure a 5V peak, a voltage level near the saturation of the amplifier so that the optimal setup point for the subsequent 2nd setup procedure, using radiation sources, can be easily reached .

The optimal voltage charge gain of our circuit is about 5V/50fC (a 5V output signal is expected when injecting on the test pin a charge of 5mV*10 pF = 50e^{-15}C by using a square wave signal generator). Even the output signal is near the saturation level of the amplifier circuit, using such a method is quite enough adequate to test that all parts of the circuit are working properly.

5.1 Setup

Some differences, due to gain mismatches and different levels of noise, may arise from unit to unit when measuring real signals due to neutron radiation.

This is why a fine adjustment is required. The gain must be setup first in order to get nearly a 3V output for energy corresponding to full peaks (both proton and triton ionization charge collected at the anode). Such level is adequate in order to avoid producing a voltage saturation and being able to count high energy cosmic events if and when these are happening.

The setup corresponding to the minimum level of charge collected requires more attention and care, as it will be explained in the following paragraphs.

The interpretation of the measurements of the voltage signal is definitely not easy and can be obtained by comparing two different measurements, using either the background radiation or a real radiation source. Both measurements are needed to have a good estimate of the gas-filled tube performances and the proper setup of the whole measurement chain.

The detector voltage pulse shape depends on the electrons and ions drift velocities, which are a function of the applied electric field and gas pressure ratio. Electrons and ions have different mobility so the charge is primarily formed by avalanche electrons collected at the anode and later on by slower ions collected at the cathode at longer time scale (1000 times longer collect time). For our purposes we can consider the contribution of slower ions as "*uncollected charge*" and seen as a fluctuation of the signal base level.

The shape of the output signal can have huge variation in voltage shape and time characteristics, due to several facts:

- Wider pulses can have the proton and triton tracks nearby to the anode wire, and narrower pulse has the tracks are almost far from the anode wire.

- Ionization is not constant along the same track.
- The non-uniform distribution of the tracks within the counter because of important neutron absorption near the cathode.
- Presence of external electronic noise.

In the following series of pictures some signal features and variations are introduced.

The figure 8 shows how different the shapes can be. Here the oscilloscope triggers on the discriminator output digital signal. No multiple pulses, otherwise evident when using the digital waveform persistence feature of the oscilloscope, are observed for each captured analogue signal. The signal must be set in order to have maximum amplitudes at around 3 V. The maximum values in the picture are just nearly above (4 V).

The Figure 9 shows a signal of less noisy amplifier.

Figure 8. The shape of the signal acquired from ^{3}He tube

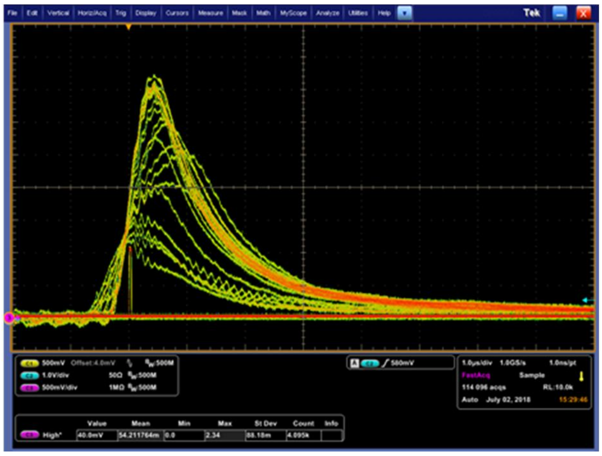
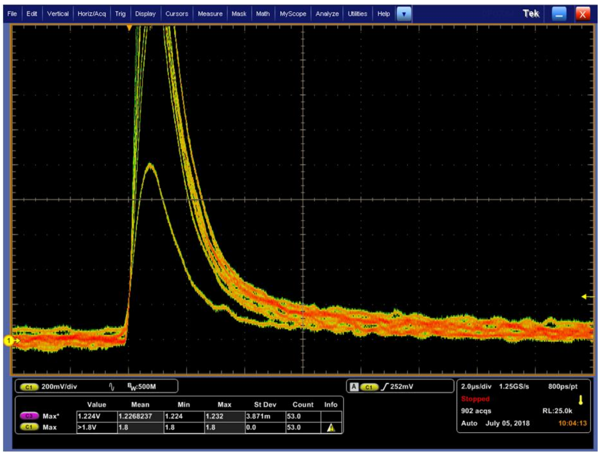


Figure 9. The low noise signal



The Figures 10 and 11 show a proper setup of the signal threshold, just below the energy corresponding to the charge collected from a triton only ionization. In order to perform this setup, the oscilloscope trigger must be set on the analogue signal channel only. The scope trigger level should range in the gap (empty signal region) in order to find the minimum voltage due to neutron radiation (charge of triton induced ionization). The Figures show setting of the signal threshold nearly at a 600-700 mV voltage level and present an estimate of the electronic noise (200 mV level or lower values).

Figure 10. Setup of the signal threshold

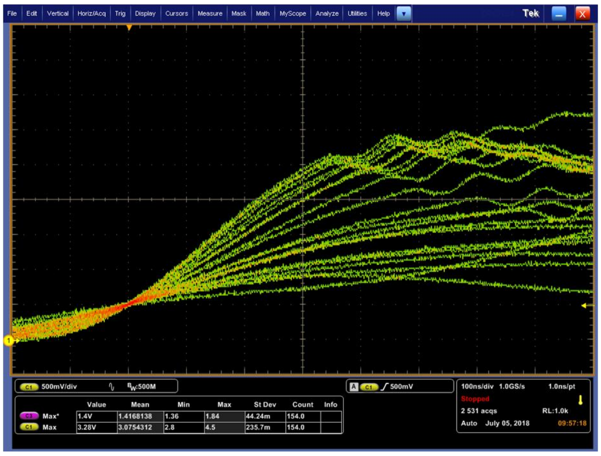
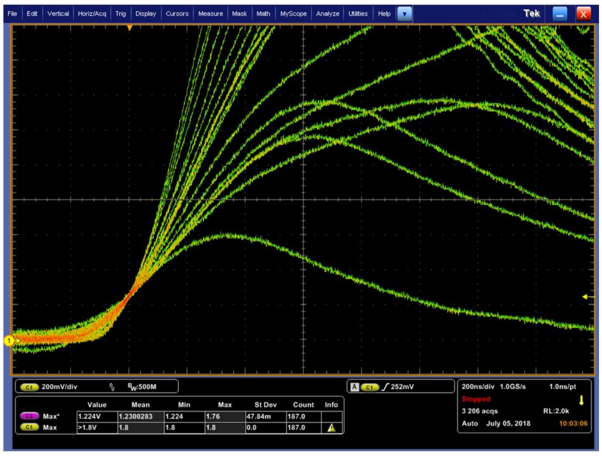


Figure 11. An estimate of the electronic noise



The output of the commercial CREMAT CR-110 charge preamplifier ,used in our design, can exhibit a not negligible negative or positive DC voltage offset at the output terminal. This DC offset can be different from model to model.

Because of this offset and because we implemented a DC-coupled Pole/Zero network, every circuit needs a manual and different calibration in order to properly discriminate between signals produced by noise or gamma-rays radiation, not to be counted, and neutron radiation to be properly counted.

A description of the procedure and how to perform it, using a digital trace persistence oscilloscope, lets everybody be able to properly operate on these sophisticated circuits.

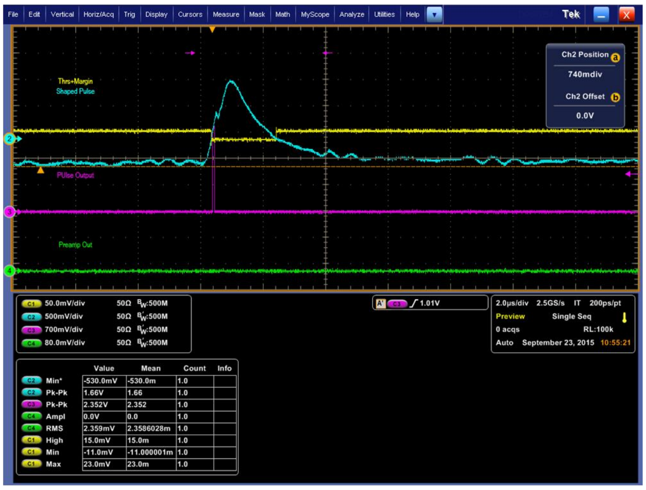
Providing such a procedure helps in reducing both manufacturing and device instalment costs, too.

5.2 Manufacturing Setup Procedure

For implementation of the manufacturing procedure use the instrumentation listed in chapter 4.1. At first to test a manufactured PCB, the manufacturing setup procedure should include the following steps:

- Apply the power supply (-9V and +9V) to the supply pins.
- Link the pulse output to channel 1 of the 2 channel 100Mhz TEKTRONIK oscilloscope.
- A 1.2 V rising edge trigger level is setup on the scope in order to capture the analogue waveform at each arrival of the digital output pulse. The digital output pulse is presented in the Figure 12 as a purple trace.

Figure 12. The print screen of the TEKTRONIK oscilloscope



The suggested procedure is:

1. Initially both the threshold levels to the ground voltage level might be set so that the output pulse is triggered by ground noise. In this case, the technician will observe multiple digital pulses.

2. The gain trimmer is the first one to be adjusted upon until a proper signal is seen at JP6 pin analogue signal output header. The light blue trace is shown in figure 12 and represents a signal at pin JP6 as it is shown in in Figure 7.

3. The threshold should be increased till no pulse at all will be seen at the output.

4. Then the gain trimmer should be adjusted in order to increase the gain and let the voltage seen at JP6 header to cross the threshold level.

5. Finally in case of double pulses appearing the final trimmer to use is the noise margin trimmer, which corresponds to the voltage shown as the yellow trace (JP4).

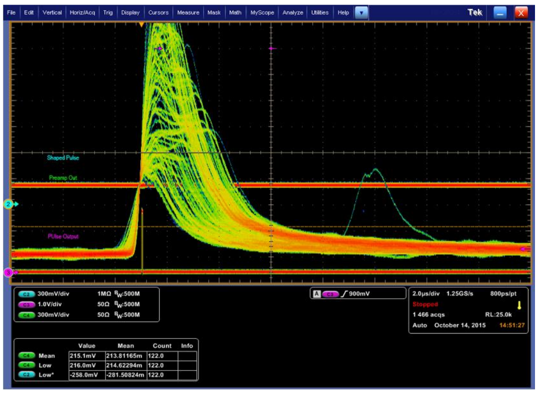
5.3 Laboratory Procedure using Radiation Sources and a digital persistence oscilloscope

For the execution of the laboratory procedure in addition to the instrumentation listed in chapter 4.1 the following is required:

- A set of at four coaxial cables connected to four channels of the TEKTRONIK oscilloscope.
- The 2.54 mm headers, to be connected on the amplifier board, should have the same colour (obtained using a coloured thermo-shrinkable wire) of the oscilloscope traces to facilitate tests.

An additional set of cables has been provided as a spare part.

Figure 13. The adjustment of a threshold level in the TEKTRONIK oscilloscope



- This adjustment is better obtained by a manual setting of the signal threshold trimmer first and then adding (superimposing) a positive noise margin using the noise margin trimmer, which acts on a diode.
- All traces must be referred to a same ground level and superimposed on the scope.

Operating properly on the three trimmers may led the technician to set a threshold level in order to observe, using a digital persistence oscilloscope, the traces shown above. It is clearly shown that each single TTL output pulse, triggered and counted just once. This means that no multiple pulses are generated and several "radiation" signals occurring on the analogue channel output can be seen. Pulses have different amplitudes and are shown superimposed on the screen, due to the persistence feature of the scope.

If the adjustment of the threshold has been performed properly, the low amplitude pulses will be absent at the background level. It is corresponding to the triton fragment charge. Pulses, lower than this set threshold level, are assumed to be generated by gamma rays or noise. The higher energy pulses appear in presence of neutron radiation source and other rare but high energy cosmic events.

Looking at the yellow trace in figure 12 or at the purple trace in figure 16 a window proportional to the discriminator's dead-time is seen. During this interval the discriminator circuit is not able to trigger in case a new pulse happens. This is not a problem if the width of this window has the same order of magnitude of several pulses shaping times (2 to 3 us) at not so high count rates.

The threshold is set in our custom circuitry by using two different trimmers; the effect of these adjustments is superimposed to the single trace that is visualized using the oscilloscope.

The threshold must be placed in the valley discriminating between the energies of gamma or electronic noise and the triton energy, looking at the well-known response of proportional counters. Some care must be taken to properly place the threshold level in the gap where no signal is seen. When triggering the oscilloscope on the digital pulses only, it can be easy to setup the threshold and to view that no multiple pulses occur.

By looking from a different perspective, and triggering on the analogue pulses shape and using the scope's trace persistence, a continuous set of pulses having different energies (from triton to proton energies) can be visualized and an gap. The gap shows absence of voltage signals between the triton energy level and the ground level is seen on the scope.

We set the voltage corresponding to charge collected from both triton and proton fragments to be nearly 3 V. The minimum energy due to only the triton charge been collected is around 1V or down to 800 mV. A threshold of 600-700 mV can be adequate but it can range from 450 to 800 mV according to what is judged the best regulation to be in presence of additional but unwanted noise. Due to the high gain of our circuit we have an ample margin to discriminate the noise and also superimpose an additional noise margin to avoid multiple pulses.

Remember that two actions are superimposed so it can be tricky to a first time user to properly setup things, because adding a noise margin can also increase the discriminator dead time.

The concept to be understood is the following:

Imagine a high jump athlete that has to overtake the rod as shown in Figure 14. In order not to hit the rod we ask her to jump a little higher (faster rise-time) , but as soon she has overtaken the rod, we put the rod at a lower level in order that she cannot inadvertently hit the rod when falling down.

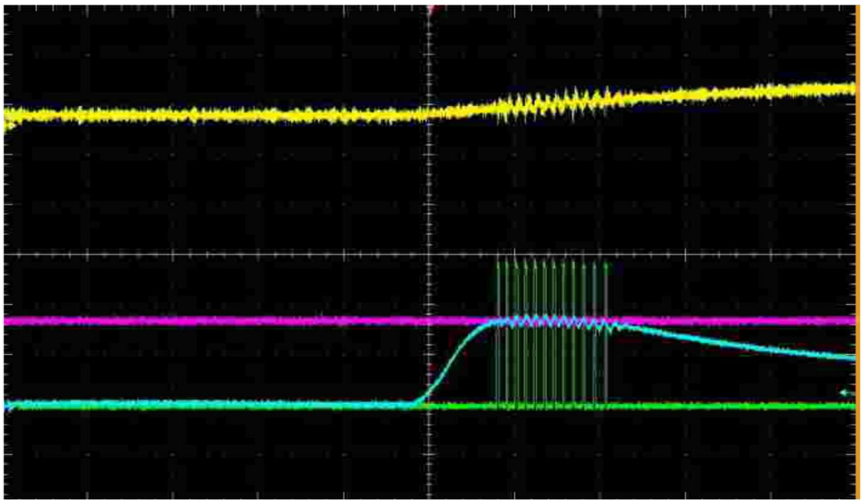
Figure 14. A high jumper

Source: https://www.athleticsweekely.com

This is the functionality performed by a diode component in the positive path of the comparator. The trick is that we used both normal and negative outputs of a comparator and the fact that the diode is switched on during the raising "jump" of the pulse and switched off during the falling down of the pulse.

In absence of such a circuit the chance of multiple pulses is real; when using such a circuit the chance of this happening is really low, because we pass pulses with enough fast rise-time in the threshold margin region, but in principle double or multiple pulses cannot be eliminated. However they can be easily discriminated by post-processing analysis of the pulse train if a time stamp has been recorded.

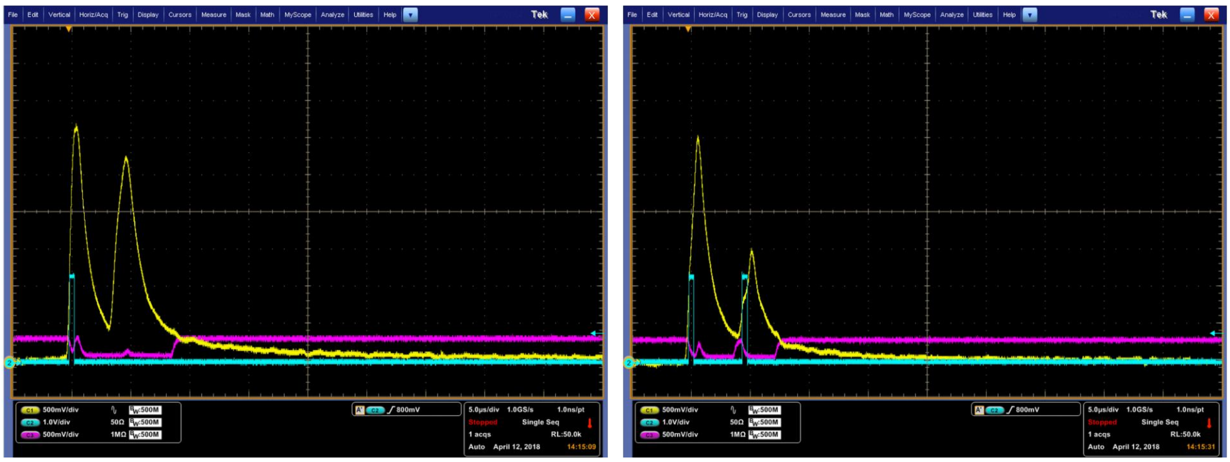
Figure 15. Multiple pulses formation



Care must be taken, however, to the time duration of the purple trace window width, proportional to several dead time effects(see figure 16) . The pulse width corresponds to the time interval when the signal is physically over the threshold level (the comparator has fired but not armed again).

The need to minimize the peak time and introduce a noise margin follows an inverse proportionality law. If the time width of the trace is too large, this means that some pulses may be lost.

Figure 16. Evidence of Updating Dead-time



The multiple pulses can arise if the noise margin is eliminated at all. This effect is normally seen by using a shift-register to have a figure of the pulse statistics.

- Connect shift register and apply the background and rate only measurement procedure.
- When this width is several times higher than the pulse width, the counts are lost in the prompt gate of the shift-register, thus reducing the efficiency of the counting chain. This means that a record of low count rates for the total count [T] will be measured.
- A wrong setup can be easily seen when the Reals+Accidentals [R+A] counts are less than the [A] counts.
- When things are setup properly using an example a ^{252}Cf source [R+A] > [A] and [T] must be high depending on the efficiency of the tube and even the ratio [R/T] should be high.

5.4 Examples of Count rate measurements

A Canberra JSR 12, 14, 15 shift register or our custom digitizing devices (TDS8 or TDS32) [9], used as list-mode devices, can be really useful to understand if anything has been setup properly either when using a radiation source such a ^{252}Cf, which produces fission events, or just measuring background radiation. Observing background low count rates and their standard deviations can also give additional indications: i.e. a tube failure, a tube having anomalous gas discharge, as it happened during tests performed at the laboratory or to provide evidence of excessive noise due to the wirings or ground bounds (poor contacts in coaxial cable ground, thus creating excessive inductance paths for fast rising pulses) or generic faults due to improperly formed ground loop (when connecting additional measurement devices).

In case of Canberra shift registers JSR 12, 14, 15 additional quality control can be done for the measurements acquired in software INCC. Quality checks are performed to measure "background" and "rate only" modes fluctuations and detected presence of multiple pulse by changing the pre-delay.

These frequency distributions are formed as follows. Every time a neutron is detected a 64 µs gate is opened, and the frequency distribution simply keeps track of how many additional neutrons are detected inside of that gate. The 1^{st} through n^{th} factorial moments (i.e. n=5) were formed although only the first two are of importance in INCC algorithm. Noise burst are evident if n > 6,7.

```
INCC 5.03

Facility: JRC ITU
Material balance area: XXXX
Detector type: JSR DRUM M.
Detector id: JRC Monitor
Electronics id: JSR14
Measurement date: 18.11.19 15:08:32
Results file name: 8BJP0832.BKG
Inspection number: 2017
Measurement option: Background
Detector configuration: Passive
Data source: Shift register
QC tests: On
Error calculation: Theoretical method
Accidentals method: Measured
Inspector name: Bogucarska
Passive comment:

Predelay: 4.50
Gate length: 64.00
2nd gate length: 64.00
High voltage: 1400
Die away time: 49.0000
Efficiency: 0.3000
Multiplicity deadtime: 45.0000
Coefficient A deadtime: 0.1580
Coefficient B deadtime: 1.5000
Coefficient C deadtime: 0.0000
Doubles gate fraction: 0.6652
Triples gate fraction: 0.4424

Number passive cycles: 613
Count time (sec): 100
```

Passive summed raw data

```
Shift register singles sum: 505030
Shift register reals + accidentals sum: 17814
Shift register accidentals sum: 276
Shift register 1st scaler sum: 0
Shift register 2nd scaler sum: 0
```

Passive summed multiplicity distributions

```
R+A sums A sums
0 490053 504773
1 12700 245
2 1858 8
3 348 1
4 76 3
5 10 0

Results

Singles: 8.239 +- 0.012
Doubles: 0.286 +- 0.002
Triples: 0.056 +- 0.002
Scaler 1: 0.000 +- 0.000
Scaler 2: 0.000 +- 0.000
```

Passive cycle raw data

```
Cycle Singles R+A A Scaler1 Scaler2 QC Tests
1 792 22 2 0 0 Pass
2 795 28 1 0 0 Pass
3 828 34 0 0 0 Pass
4 830 33 0 0 0 Pass
5 794 31 0 0 0 Pass
```

```
6 812 33 1 0 0 Pass
7 807 32 0 0 0 Pass
8 845 22 1 0 0 Pass
9 812 22 1 0 0 Pass
10 795 31 1 0 0 Pass
11 852 40 1 0 0 Pass
12 808 35 4 0 0 Pass
13 802 31 0 0 0 Pass
14 815 13 1 0 0 Pass
...
650 885 24 0 0 0 Pass
651 851 31 0 0 0 Pass
```

Passive cycle rate data

```
Cycle Singles Doubles Triples QC Tests
1 7.920 0.200 0.040 Pass
2 7.950 0.270 0.030 Pass
3 8.280 0.340 0.030 Pass
4 8.300 0.330 0.100 Pass
5 7.940 0.310 0.050 Pass
6 8.120 0.320 0.080 Pass
7 8.070 0.320 0.130 Pass
8 8.450 0.210 0.020 Pass
9 8.120 0.210 0.010 Pass
10 7.950 0.300 0.030 Pass
11 8.520 0.390 0.050 Pass
12 8.080 0.310 0.008 Pass
13 8.020 0.310 0.040 Pass
14 8.150 0.120 0.020 Pass
...

650 8.850 0.240 0.000 Pass
651 8.510 0.310 0.040 Pass
```

Passive multiplicity distributions for each cycle

```
Cycle 1 R+A A
0 773 790
1 17 2
2 1 0
3 1 0

Cycle 2 R+A A
0 770 794
1 22 1
2 3 0

Cycle 3 R+A A
0 797 828
1 28 0
2 3 0

Cycle 4 R+A A
0 803 830
1 24 0
2 1 0
3 1 0
4 1 0

Cycle 5 R+A A
0 768 794
1 21 0
2 5 0

Cycle 6 R+A A
0 785 811
1 23 1
```

```
2 2 0
3 2 0

Cycle 7 R+A A
0 784 807
1 17 0
2 4 0
3 1 0
4 1 0

Cycle 8 R+A A
0 825 844
1 18 1
2 2 0

Cycle 9 R+A A
0 791 811
1 20 1
2 1 0

Cycle 10 R+A A
0 767 794
1 25 1
2 3 0

Cycle 11 R+A A
0 817 851
1 30 1
2 5 0

Cycle 12 R+A A
0 779 807
1 24 0
2 4 0
3 1 0
4 0 1

Cycle 13 R+A A
0 775 802
1 23 0
2 4 0

Cycle 14 R+A A
0 804 814
1 9 1
2 2 0

Cycle 15 R+A A
0 855 882
1 22 0
2 4 0
3 1 0
...
Cycle 650 R+A A
0 861 885
1 24 0

Cycle 651 R+A A
0 824 851
1 23 0
2 4 0
```

Outliers were found in the measurements. But after upgrade of electronic circuits and application of this calibration procedure, the reported results show a significant decrease of the noise outliers.

Some of the outliers could correspond anyway to acceptable measurements, because having set a three sigmas exclusion criteria for doubles may be too restrictive.

An example of such situations is depicted in the following records. An investigation is underway to understand the nature of these events, because they could depend on a particularly noisy amplifier unit or to the way pulses coming over parallel lines are mixed on a single line.

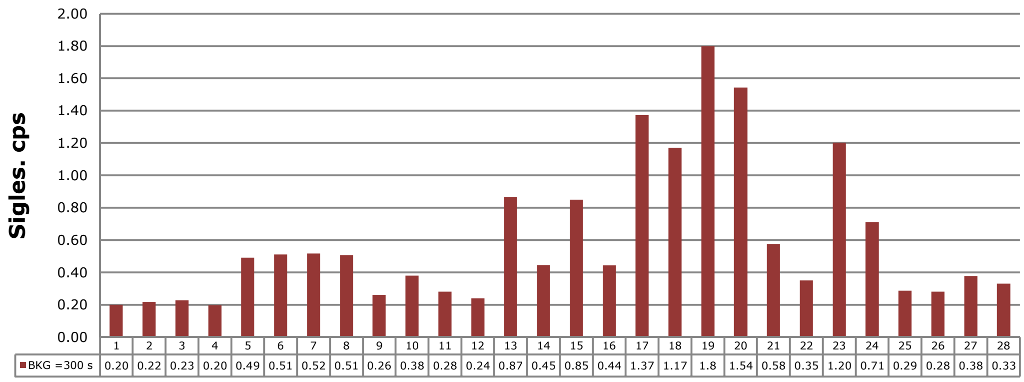
This effect could not anyway be visible on a standard OR-chain, because nearly coincident pulses would be enveloped in a single pulse. Our novel "list-mode" devices TDS8 and TDS32 will prove particularly useful with respect Canberra JSR12, JSR14, JSR15 analyzers in detecting bursts of noise by a post-process analysis of the recorded time stamps. [9]

```
Passive cycle raw data
Cycle Singles R+A A Scaler1 Scaler2 QC Tests
352 787 22 1 0 0 Pass
353 827 45 0 0 0 Fail outlier test
354 808 21 0 0 0 Pass

Passive cycle rate data

Cycle Singles Doubles Triples QC Tests
352 7.870 0.210 0.030 Pass
353 8.270 0.450 0.372 Fail outlier test
354 8.080 0.210 0.020 Pass
Cycle 352 R+A A
0 768 786
1 16 1
2 3 0
Cycle 353 R+A A
0 800 827
1 18 0
2 4 0
3 4 0
4 0 0
5 0 0
6 0 0
7 1 0
Cycle 354 R+A A
0 789 808
1 17 0
2 2 0
```

Several hundred cycles of 100s background measurements from the passive drum monitor performed by the use of INCC software are shown below.

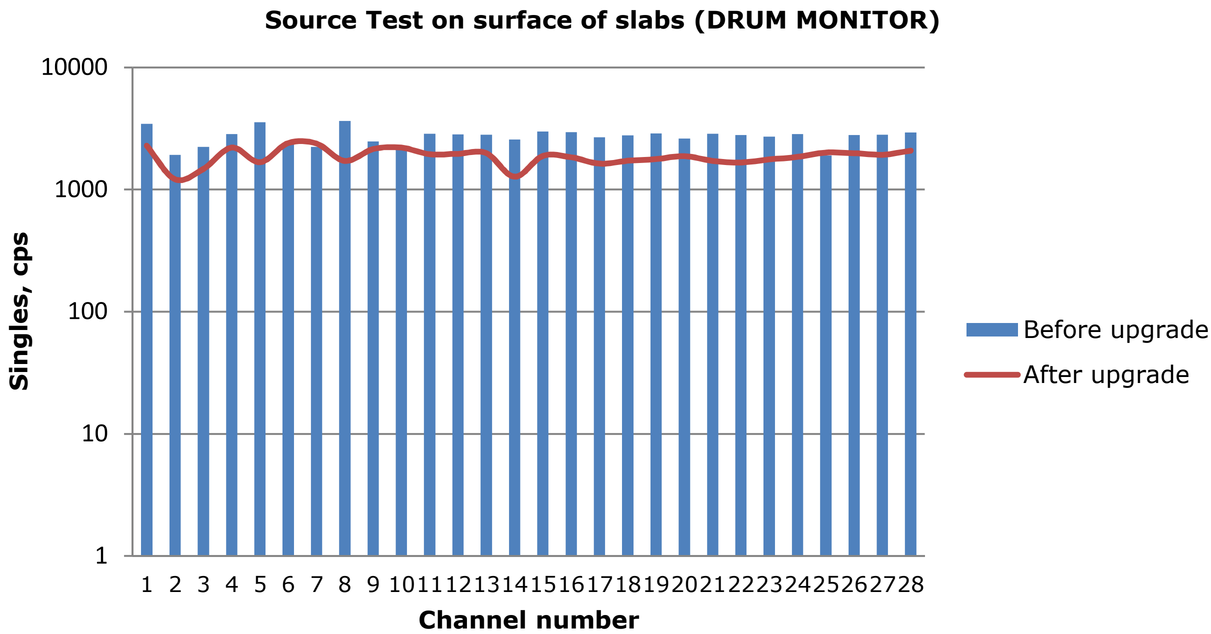
It is expected to get output signal of all 28 channels present in drum monitor in coherent way for range of channels from 5th to 28th. The channels from 1st to 4th are corresponding to slabs allocated in top and in bottom of drum monitor. The ^{3}He tubes have different length. The figure 17 shows background single counts variations acquired in each channel separately. Every measurement consisted of at least 3 repetitions of 100s.

Figure 17. Background counts after upgrade of amplifiers



The Figure 18 shows a singles counts measured in July 2015 before upgrade of amplifiers and measurements performed in September 2018 after upgrade of amplifiers. Source' position was on the module' surface and in the centre of every module. Both left and right sections of the module were measured. Every measurement consisted of at least 3 repetitions of 100s. The spontaneous fission of ^{252}Cf source was used as neutron radiation source. To compare the measurement results, the decay correction was applied.

Figure 18. Comparison singles counts before and after upgrade of amplifiers in a logarithmic scale



6 Conclusions

An inexpensive tiny board, containing an analogue charge amplifier with a simple pulse shaper (a pole/zero network) and a digital discrimination circuit has been designed. The board can be easily housed in the drum monitor and slab counters brass modules.

The novel digital discriminator circuit, even not being able to virtually eliminate all possible multiple pulses for the reasons explained before, greatly reduced their effects sometimes at the expense of a little increase in overall dead-time.

The circuit proved to be really insensible to temperature variations and quite immune to levels of electric noise.

One reason of very rare but present spikes of noise in the measurement performed using INCC is to be further investigated. The use of a multiple stage low-pass filter on the high-voltage rails proved to be effective in reducing rare but wrong measurement records.

An analogue differential cascode charge amplifier has been simulated and is going to be tested on a real environment.

The goal of designing such a new inexpensive but low-noise circuitry will be to use an amplifier on top of each proportional counter tube so as to reduce the overall dead-time.

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List of abbreviations and definitions

AWG	Arbitrary Waveform Generator
TTL	Transistor Transistor Logic
VHDL	Very High Speed Hardware Description Language
USB	Universal Serial Bus
FPGA	Field Programmable Gate Arrays

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Annex 1. Charge sensitive preamplifiers

CREMAT Inc. produces 4 different types of non-resettable charge sensitive preamplifiers, whose characteristics are summarized in the Table 3.

Table 3. Features of non-resettable charge sensitive preamplifiers manufactured by Cremat

Feature	Unit	CR-110	CR—111	CR—112	CR-113
ENC (rms)	electrons	200	630	6800	24000
	fC	0,03	0,01	1,1	4
Gain	V/pC	1,4	0,15	0,015	0,0015
Risetime	ns	7	3	6	20
Decay Time constant	us	140	150	50	50
Maximum charge per event	electrons	$1{,}3*10^{7}$	$1.3*10^{8}$	$1{,}3*10^{9}$	$1{,}3*10^{10}$

Only model CR-110 was taken into considerations. A Pole/Zero network was designed as the output of the CREMAT preamplifier [2]. Design requirements are for three different shaping times to be implemented: 500 ns(default) , 750ns and 1 us. These different values can be achieved soldering different capacitors over the PCB.

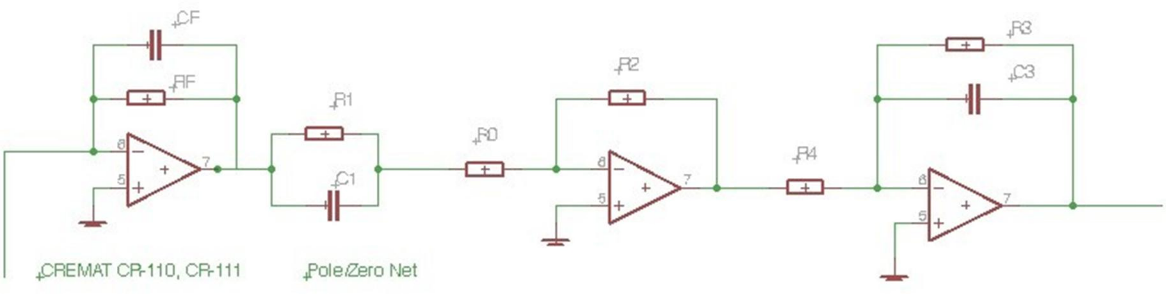
A brief theoretical consideration about the expected waveform of the output pulse signal is given below.

Preamplifier DC Gain = k Q / CF

P/Z Net DC Gain = - R2 / (R0+R1)

Integrator DC Gain = - R3 / R4,

where R0, R1, R2, R3 and R4 are relevant resistors



A Pole/Zero network is used to compensate the CREMAT Integrator time constant and an additional integrator is used to obtain a $H(s) = 1 / (s+ \tau)^2$ frequency response, so that the time domain output signal will be : $v_o(t) = t/\tau \, e^{-t/\tau}$ where τ = Shaping Time time-constant.

The maximum output signal , corresponding to a time equals to the shaping time, will be:

Vmax = K * Q/C_f *$R_2/(R_0+R_1)$ *R_3/R_4 *1/e where K is the gas multiplication factor, Q the injected charge, value of the constant e ~= 2.78 and $R_0 << R_1$

Q is approximately 764 keV / 31.8 eV [ion pairs] * 1.602 e^{-19} [electron charge] * K [Gas Multiplication Factor , where K = 15 … 100] .

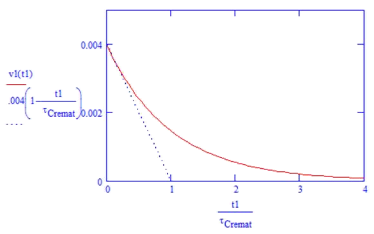
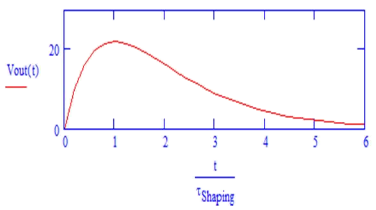
The output waveform is obtained by a simplification of the frequency response taking:

1st Constraint : $R_1 . C_1 = R_f . C_f$ = CR110 Time constant.

2nd Constraint : $(R_0 \| R_1) * C_1 = C_3 . R_3 = \tau$ where τ= Shaping Time constant.

Please consult PCB layouts for the actual location and correspondence of components

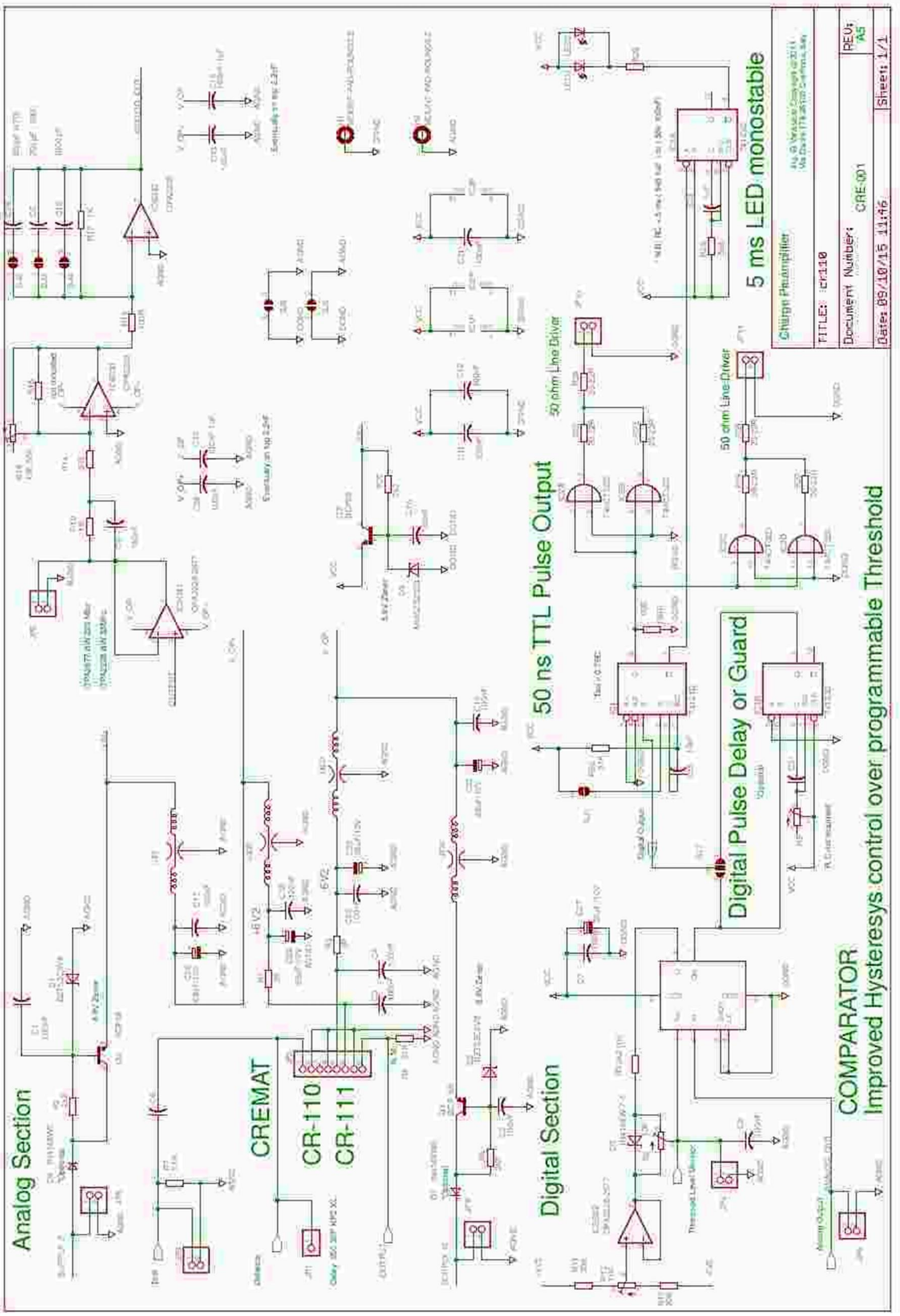
Simulation

	$v1(t1) := K\cdot\frac{Q}{C_f}\cdot e^{\frac{-t1}{\tau_{Cremat}}}$	$V1(s) := \frac{K\cdot Q\cdot R_f}{1+s\cdot R_f\cdot C_f}$
	$V2(s) := V1(s)\cdot\frac{R_2}{R_0+R_1}\cdot\frac{1+s\cdot R_1\cdot C_1}{1+\frac{s\cdot R_0\cdot R_1}{R_0+R_1}\cdot C_1}$	$V2(s) := K\cdot Q\cdot R_2\cdot\frac{R_f}{R_0+R_1}\cdot\frac{1}{1+s\cdot\frac{R_0\cdot R_1}{R_0+R_1}\cdot C_1}$
	$V\_out(s) := K\cdot R_f\cdot Q\cdot\frac{R_2}{R_0+R_1}\cdot\frac{1}{\left(1+s\cdot\frac{R_0\cdot R_1}{R_0+R_1}\cdot C_1\right)}\cdot\frac{R_3}{R_4}\cdot\frac{1}{1+s\cdot R_3\cdot C_3}$	
$\tau_{Shaping} := \frac{C_f\cdot R_f\cdot R_0}{R_0+R_1}$	$Vout(t) := \frac{Q\cdot K}{C_f}\cdot\frac{R_2}{R_0}\cdot\frac{R_3}{R_4}\cdot\frac{t}{\tau_{Shaping}}\cdot e^{\frac{-t}{\tau_{Shaping}}}$	

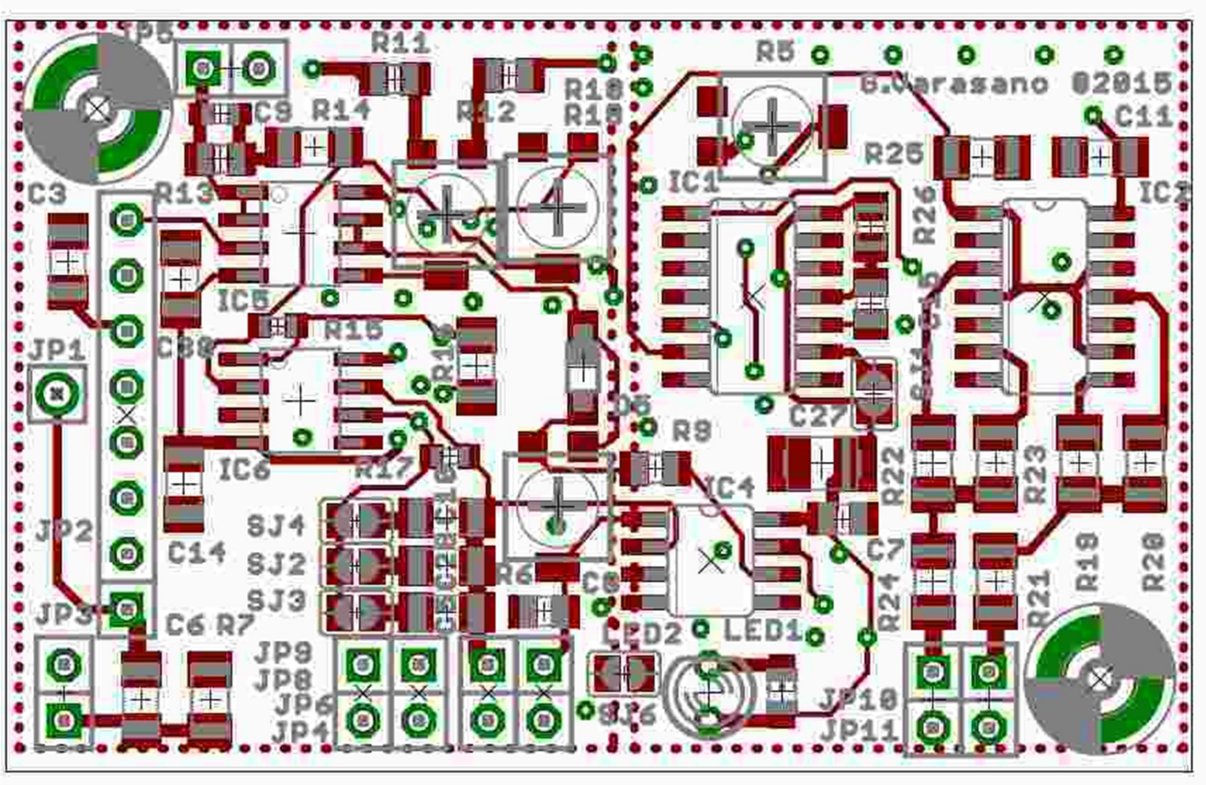
The following table summarizes the final values used for resistors and capacitors:

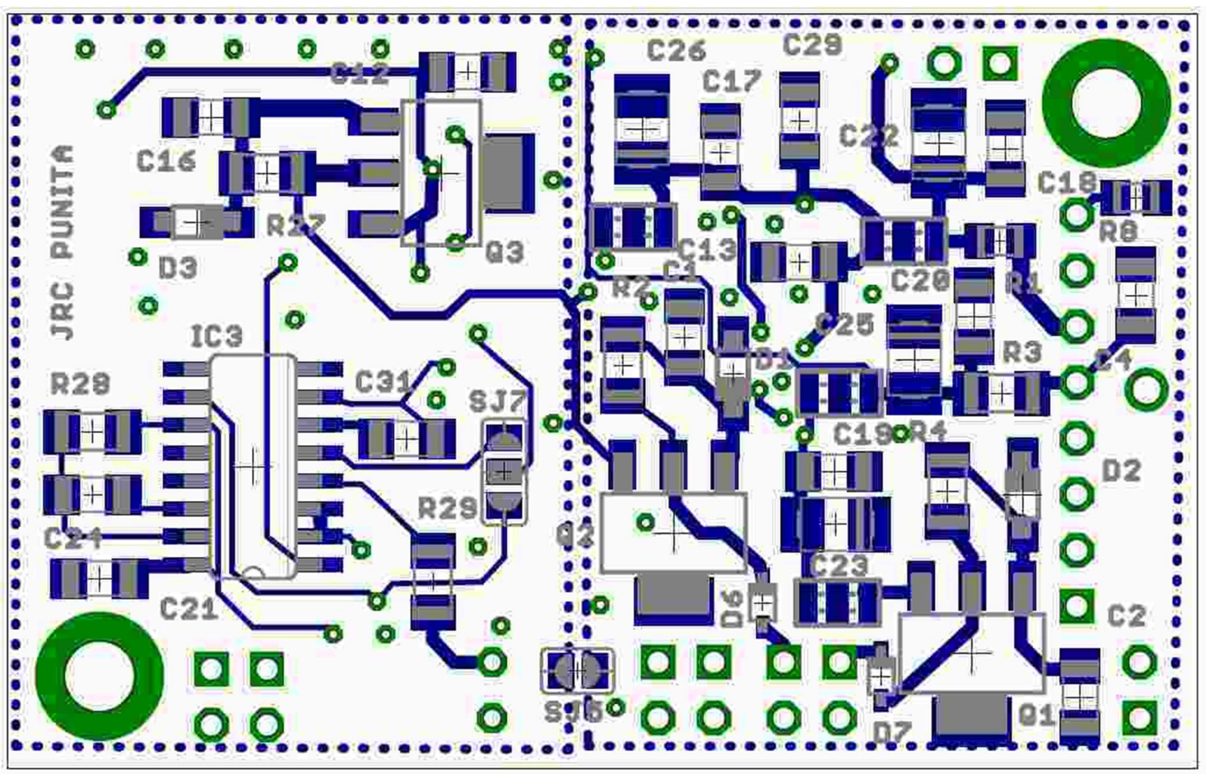
Cremat 1st Integrator		**Pole/Zero Network**				**2nd Integrator**		
R_f [Ω]	C_f [pF]	R_0 [Ω]	R_2 [Ω]	R_1 [kΩ]	C_1 [nF]	R_3 [kΩ]	C_3 [pF] [ns]	R_4 [Ω]
10^8	1.4	3.3	0-200	1	140-150	1	500 = τ	100

Annex 2. - Schematics

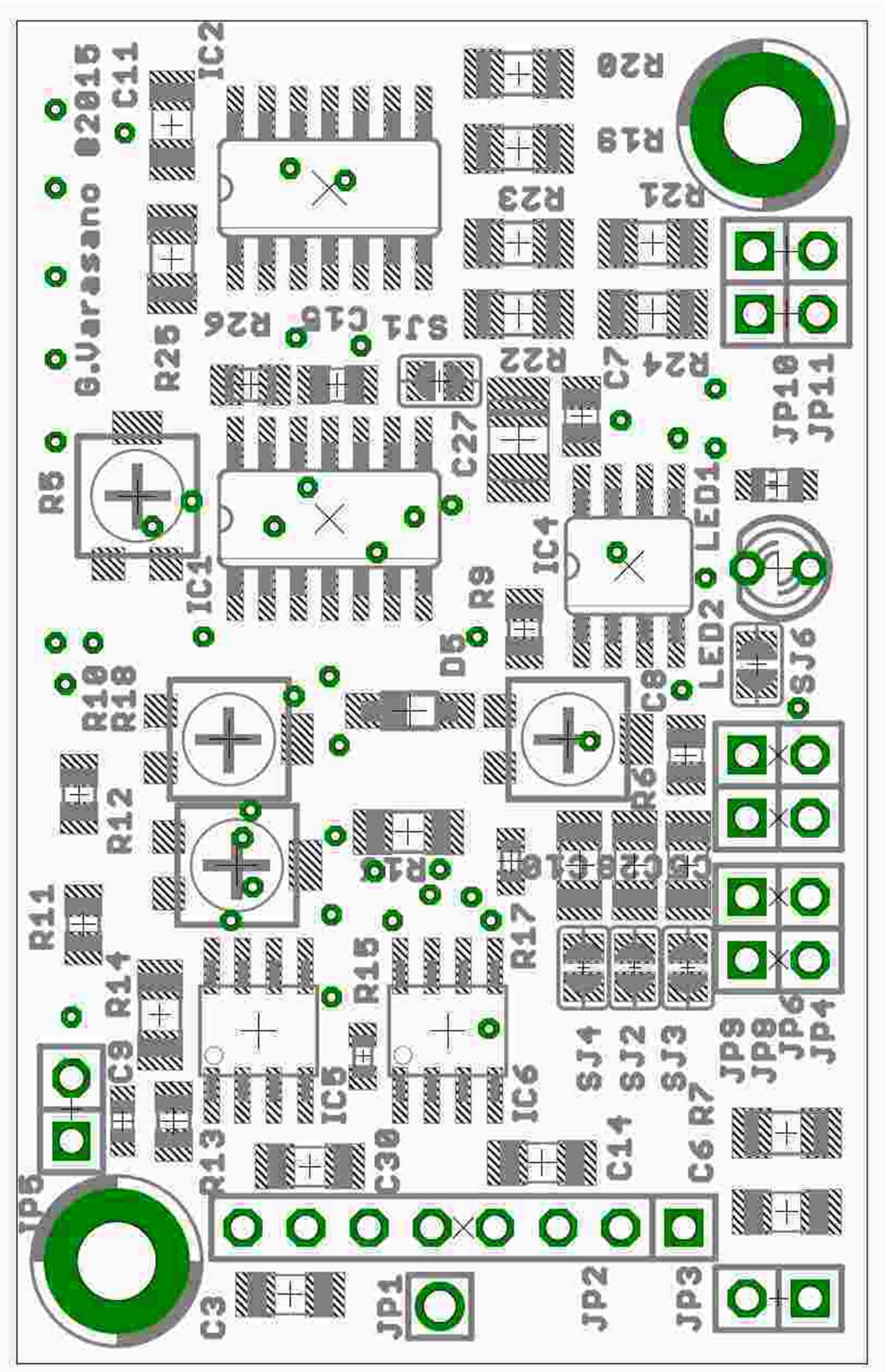


Annex 3. – Printed Circuit Board Layout





Annex 4. – Circuit Topographical View



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