University of Michigan

NERS 799

Room temperature TlBr detector

Laboratory Report

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1 Preamble

This report intends to present in a concise way the register of the project taken as a dedicated study (NERS 799) by the student Luiz Flavio Dias da Costa Azevedo (UMID 09339829), master student in the Nuclear Engineering and Radiological Science (NERS) department. The study and experimental tests were performed at the Knoll Laboratory (NEL 3rd floor) under advisor and instruction of Dr. Zhong He.

2 Introduction

Coming from the industry of Nuclear Power Plant (NPP) Design, and mainly from the Instrumentation and Control System point of view, a NPP to operate safely need numerous parameters and indicator of the good functioning of processes among which temperature, pressure, flow and radiation. The radiation measurements vary from the ones relevant to keep the safety function of containment to the radio protection around an inside the installation, helping to identify, control and mitigate possible release of radioactive material out of the the primary loop on the first case and keeping operators and workers in a safe level of exposition.

Along the way of finding radiation, being able to quantify its energy and damage and to characterize its source has been a challenge in which different technologies and methods of detecting radiation have been improved with still room for findings that could help to solve problems or limitations of the ongoing technologies at the market regarding for example, space, shielding for background and efficiency/resolution.

Radiation detection technologies involve different methods and materials for making its energy measurable due to different kinds of radiation with distinct physical and electrical properties and also specific energies since we have for instance heavy charged particles, high energy electrons and neutral ones like neutrons and gamma.

Among those materials and technologies, semiconductors has been used with very good resolution due to its density and often composed by elements with atomic number (Z) very high what increases interaction of the radiation with the material that is the first step to detection. Often one down side of the use of semiconductors has been the need for cryogenic-cooling. The use of room temperature semiconductors was one of the advances and has been used successfully with CZT.

Another promising semiconductor with potential to a room temperature gamma ray detector due to the high Z number of components and so a high stopping power and probability of interaction, its high density (7.56 g/cm3) and the much wider band gap (2.68eV) to the excitement and generation of free-moving electrons with radiation interaction, is the Thallium Bromide (TlBr) [1]

Degradation of TlBr under bias and temperature has being studied since its stability and performance has been an issue limiting its potential as a detector. K. Kozlov et al. [1] mention that its electrical properties can be debilitated by impurities and crystal defect structure, issues that can be and has been addressed in improving the quality of manufacturing, however polarisation is commonly observed. According reference [2] one of the causes can be ionic conductivity that creates "microinhomogeneity" activated by the electric field and non-equilibrium carrier generation. Figures of this work [2] show that hole drift mobility (μ) decreases with the increase of Temperature ($\mu \; \alpha \; 1/T$) while carrier concentration increases. In addition in reference [3] Figure 3, we can notice the conductivity decreasing with rising temperature, although after 300K (27°C) this trend inverts. J. Vaitkus et al. [3] also concluded that creation of dendrite structures and the ionic conduction mechanism inside TlBr at temperatures higher than 250 K were due to Tl+ ions, through charge transfer.

Poor resolutions in TlBr detectors were reported to be due to ballistic deficit resulting from incomplete signal processing connected to the small mobility of carriers (electrons and holes) through TlBr crystals [4]. Such connection is explained [5] by the fact that slow mobility leads to long transit times that can increase the lost of information through ballistic deficit. On those cases, a longer shaping time is necessary for better resolutions what also increases pulse pile up and low frequency noise where the latter was also observed in my data.

Although some issues, crystals of TlBr from RMD have shown Cs-137 662keV peak with about 1.5% energy resolution (FWHM) [6]

Not addressed in this study but the polarisation problem in TlBr is also affected and increased degradation on performance at higher temperatures than the room temperature of 25 degrees centigrade [1],[7]

Once found and corrected the limitations of the use of Thallium Bromide as a detector with acceptable resolution and good perform under industrial/commercial operational temperatures and durability over time, it could be a reasonable, inexpensive, small sized, alternative gamma-ray spectrometer for a lot of plants and applications

3 Equipment and Setup

The experiments and tests was basically performed with H3DD S-Series detector/ASIC and SOLO-R DAQ system based on IDEAS VAD-UMv2.2 ASIC and crystal of TlBr from RMD.

3.1 H3D S-series

The H3D S-Series Spectrometers, commercial products with good resolutions using CZT, were used in this case with TlBr crystals to verify their performance with this device which specifications can be found at *https://h3dgamma.com/S100Specs.pdf*. The spectrometers named Alger, Alcona and Murray were used with the respective crystals according to the following table.

System	**Detector**
Murray	935-38AS3
Alger	208BS2
Alcona	212AS2(R)

Table 1: H3D S-series devices and crystals

Measurements of 24h with no source were taken for each device and before each round of measurements with the same system (Murray, Alcona, Alger) and was used as background and so discounted for each measurement when processing the data. Calibration with C-137 source were performed to accommodate the x-axis with the keV (kilo electron-volt) scale. Different sources were used in order to study the characterization, resolution and accuracy of TlBr crystal operated in the H3DD systems, based on typical photopeaks of sources like Co-60, Am-241, Cs-137 and Ba-133. Each measurements was taken for time necessary to collect at least 200,000 counts, leading top longer times on farther distances and also depending on the activity of each source used. The curving and analysis were only applied at the spectrum that could evidence a photopeak.

3.1.1 Curving

For the learning process and calculation of resolution of the TlBr detector used on H3D systems for CZT, the data obtained was processed and curved with Gaussian in excel, obtaining the peak centroid, and resolution in full width at half maximum (FWHM)

3.2 Orion SOLO-R

The SOLO-R (ASIC 7038) circuit developed by the Orion Group as used to test some crystals either in comparison to the results on the other ASIC or to check performance on different high voltage applied or even to make the measurements in the furnace exposing to different temperatures than room temperature.

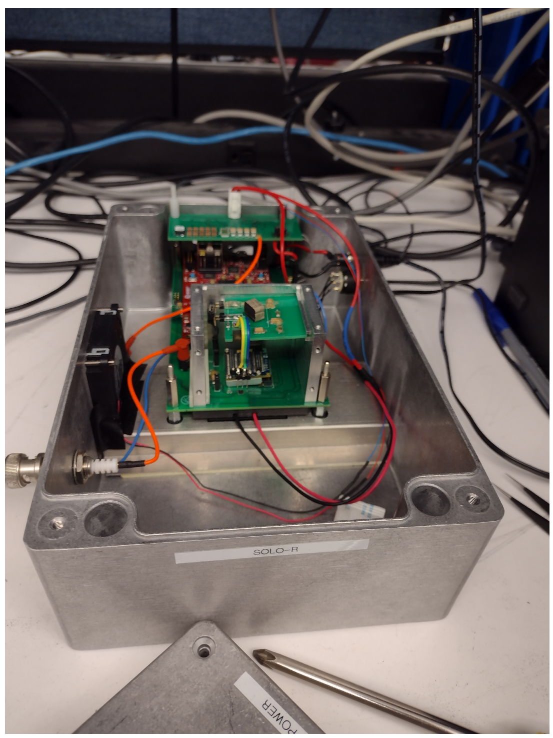


Figure 1: Orion SOLO-R

The crystals used were 203BS2(R), 212BS2(R), 168CS2(R), 208BS2(R), 212AB1, 212AB2

In most of the measurement Cs-137 was used and different voltage applied to observe the difference on results and stability after time and over some voltage level.

3.2.1 Data Acquisition (DAQ)

To set up the measurements, Orion Solo Usage procedure were followed for every round with the help of the software OrionUMDAQ.

Following is an image of the settings for a 6X6 crystal as 168CS2(R)

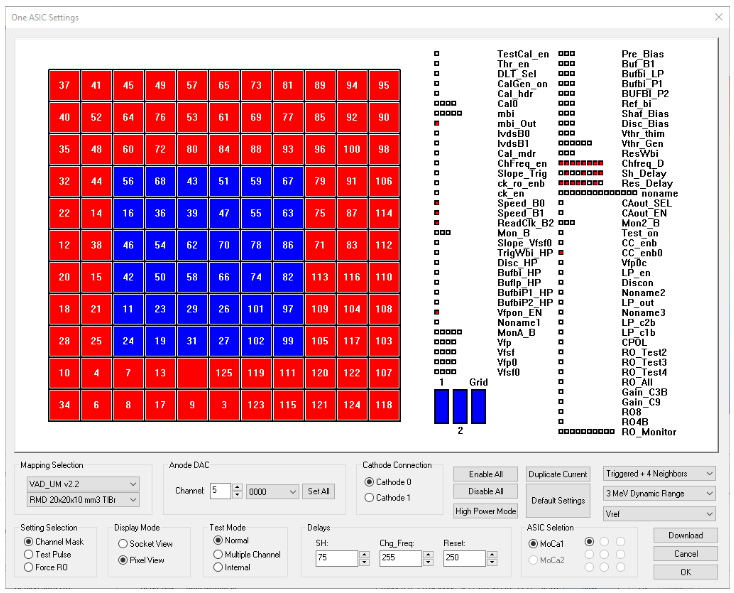


Figure 2: ASIC settings

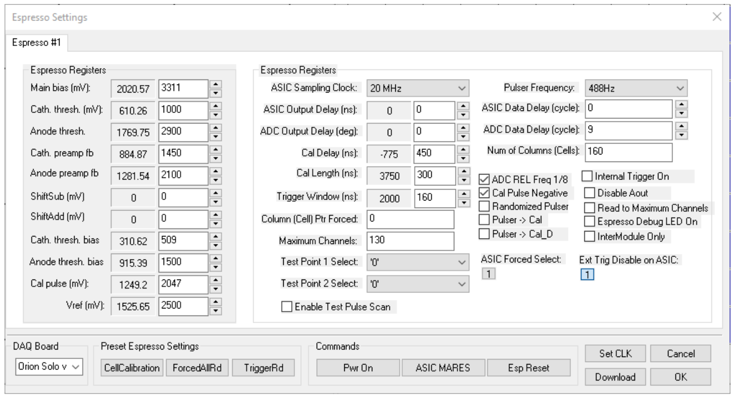


Figure 3: Espresso settings

3.2.2 Temperature behavior

In order to start an study on how TlBr behaves as a detector on temperature above room temperature and how the temperature affects the peak centroid and resolution, the system SOLO-R was assembled inside a furnace in which the varied temperatures were set. For all the cases Cs-137 was used as the source and only 2 crystals were submitted 168CS2(R) and 212AB2.

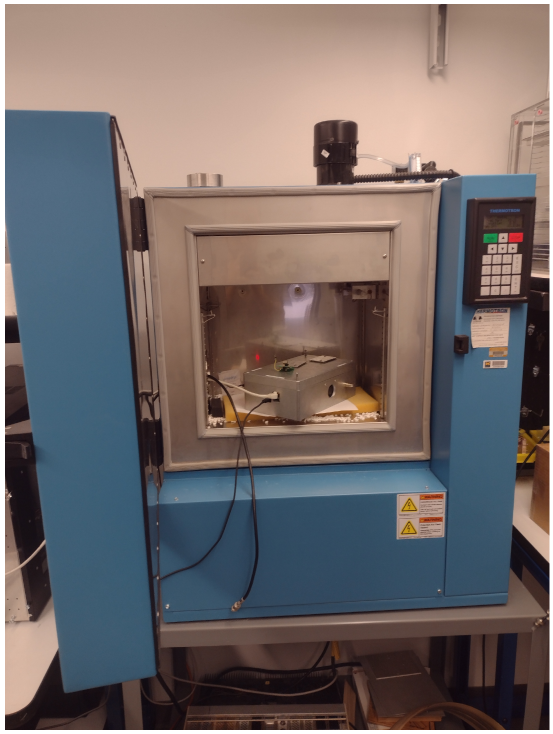


Figure 4: Temperature behaviour setup

4 Collected Data

The Data was collected through Polaris when using H3D system and Orion SOLO DAQ when using SOLO-R. The data from Polaris was mainly process in Excel but also in Polaris Waveform Analyzer. The data from SOLO was process through MATLAB code develop by Erik Hall and adapted to the purposes in case.

With the intention of checking the capability of characterization of the source for different distances (2, 8, 32, 128 in) the collected data with the H3D system was processed in Excel. A 24h measurement without any source was made in order to give the background counts there was subtracted in the data processing.

In order to study the TlBr crystals' stability and consistency in results with different applied voltage and over time, the measurements made with SOLO-R were processed in MATLAB generation plots like all pixel spectra, overall spectrum, depth curve.

Regarding some orientation on the analysis of the multichannel plots, the following figure names the lines and rows as well as each channel in their position so they can be referred by their channel number.

Ch-Pix Map: Polaris/RMD

4/8	56	68	43	51	59	67
5/7	16	36	39	47	55	63
6/6	46	54	62	70	78	86
7/5	42	50	58	66	74	82
8/4	11	23	29	26	101	97
9/3	24	19	31	27	102	99
	3/C	4/D	5/E	6/F	7/G	8/H

Figure 5: Channel/pixel Map

5 Data Analysis

5.1 H3DD systems and sources

Among all the tested the Murray (935-38AS3 TlBr crystal/detector) was the one who presented the best results and is displayed here as an example.

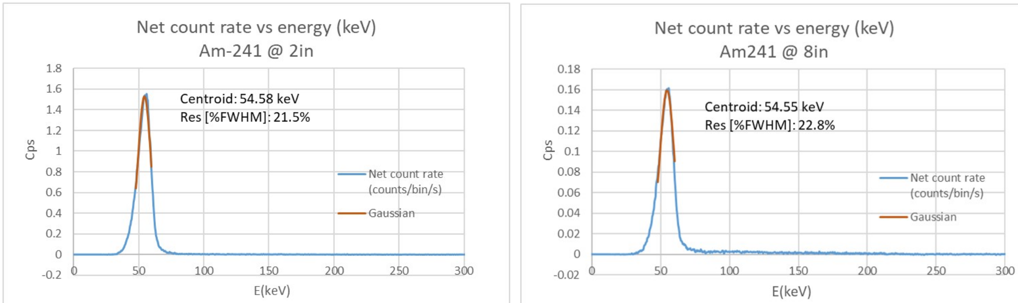


Figure 6: Murray and Am-241, 2 and 8 inches distant

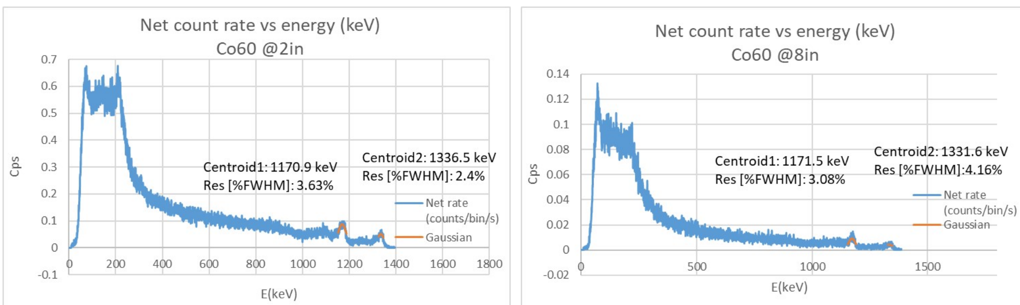


Figure 7: Murray and Co-60, 2 and 8 inches distant

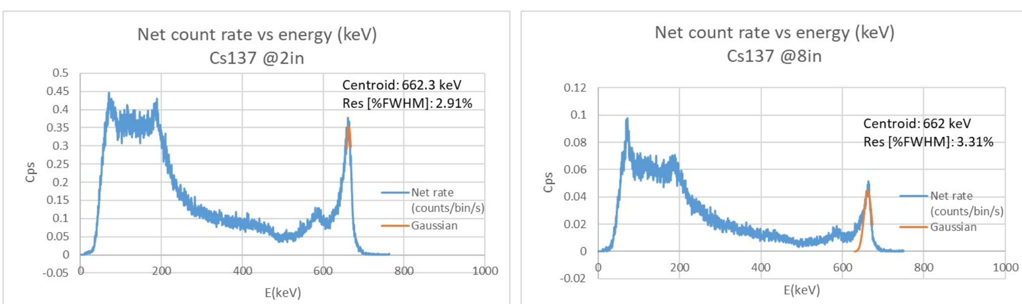


Figure 8: Murray and Cs-137, 2 and 8 inches distant

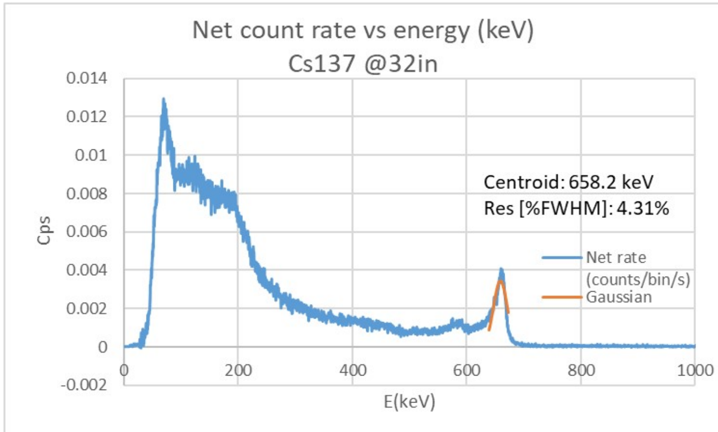


Figure 9: Cs-137, 32 inches distant

The lack of spectra with the distances of 32 in and 128 in with most of the sources means that no significant photopeak was observed. We can observe that through distances of 8 inch (and for Cs-137 32 in) the detectors with Thallium Bromide were able to present the characteristic photopeaks like the 662 keV for Cs-137, 59 keV for Am-241, 1173 and 1332 keV for Co-60 with decent resolutions and slight deviation on the peak centroid energy with the exception of the Americium source.

5.2 SOLO-R

The collected and processed data of measurements with SOLO-R will be presented by crystal. The first measurements and data processing was very helpful to learning how to setup the measurements, the variables and how the software and codes work and the start to understand the dynamic of the detector and study properly its properties and how to improve its performance.

5.2.1 208BS2(R), 11x11, 1.7 mm pixel pitch, 1 cm thick

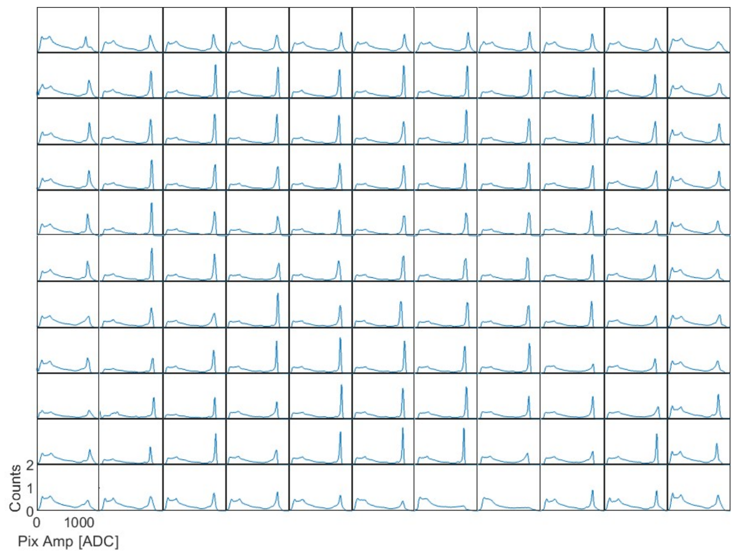


Figure 10: 208BS2(R) at HV=-1000V around 24h exposed to Cs-137, spectrum by pixel

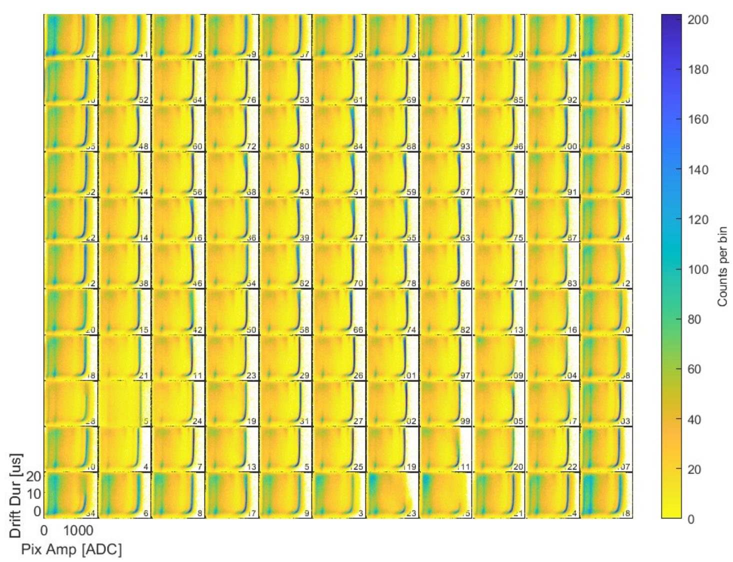


Figure 11: 208BS2(R) at HV=-1000V around 24h exposed to Cs-137, depth curve

5.2.2 212AB1, 11x11, 1.7 mm pixel pitch, 1 cm thick

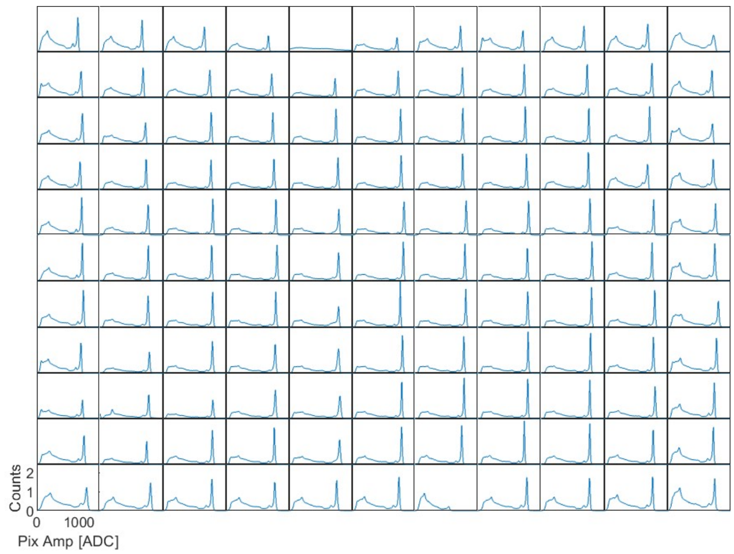


Figure 12: 212AB1 at HV=-1000V around 24h exposed to Cs-137, spectrum by pixel

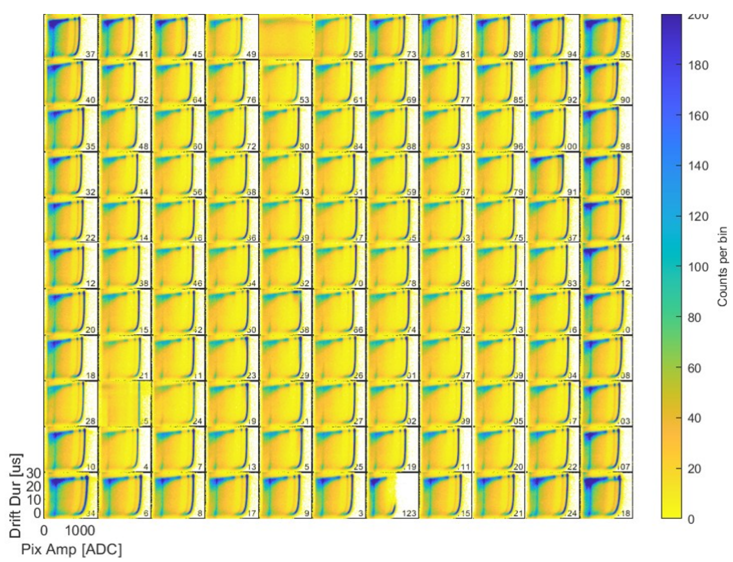


Figure 13: 212AB1 at HV=-1000V around 24h exposed to Cs-137, depth curve

This data was also processed with the help of the Polaris Waveform Analyzer, where we can see resolution in 1.79% on the 662keV photopeak.

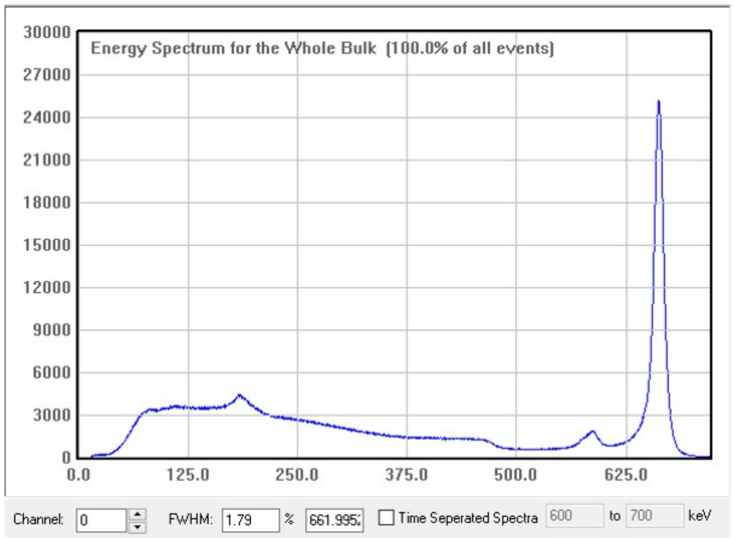


Figure 14: 212AB1 at HV=-1000V around 24h exposed to Cs-137, spectrum by Waveform Analyzer

Also the leakage current can be an important information on the analysis.

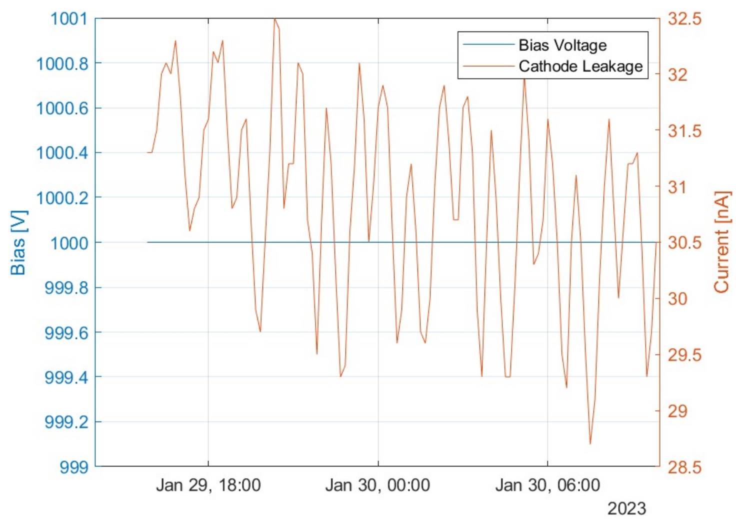


Figure 15: 212AB1 at HV=-1000V around 24h exposed to Cs-137, Leakage current vs time

5.2.3 193BS4-1, 6x6, 1.7 mm pixel pitch, 1 cm thick

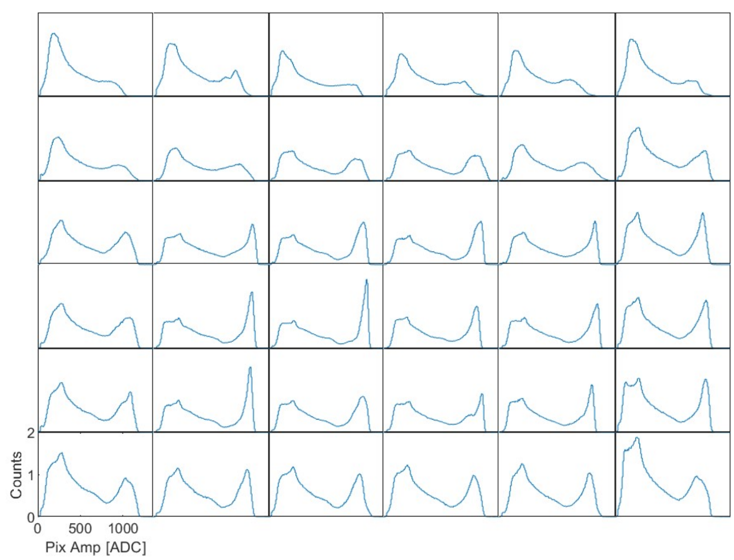


Figure 16: 193BS4-1 at HV=-1000V around 24h exposed to Cs-137, spectrum by pixel

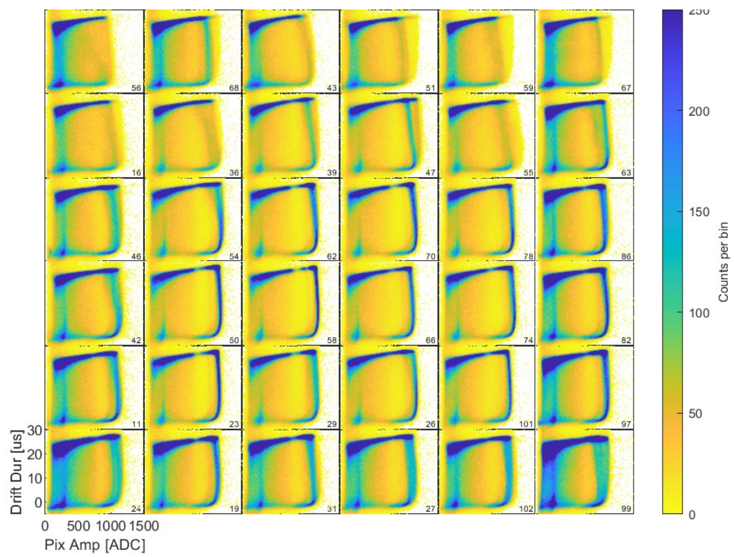


Figure 17: 193BS4-1 at HV=-1000V around 24h exposed to Cs-137, depth curve

5.2.4 168CS2(R), 6x6, 1.7 mm pixel pitch, 1 cm thick

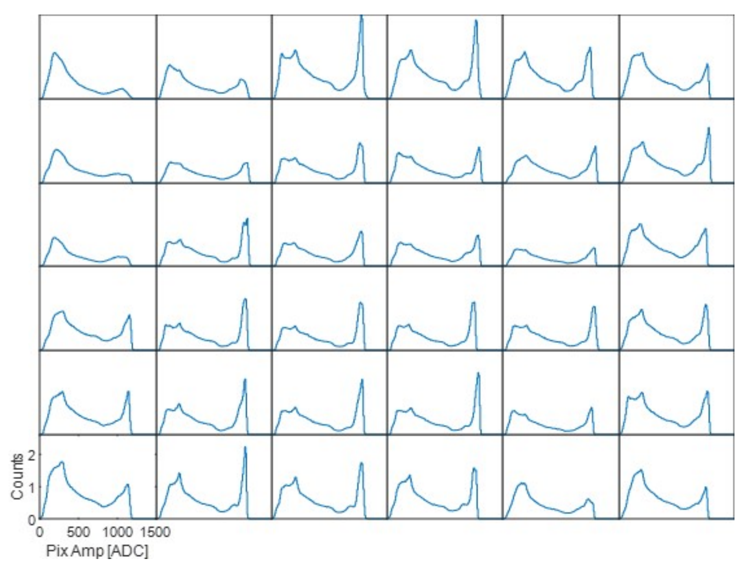


Figure 18: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137, spectrum by pixel

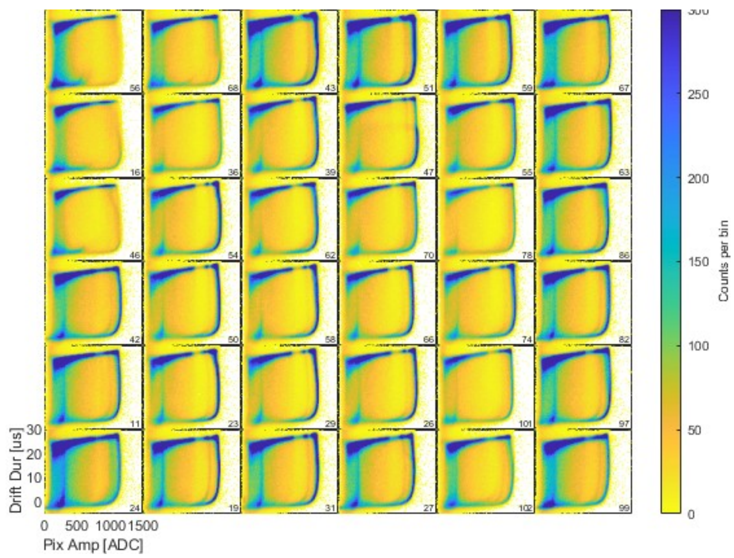


Figure 19: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137, depth curve

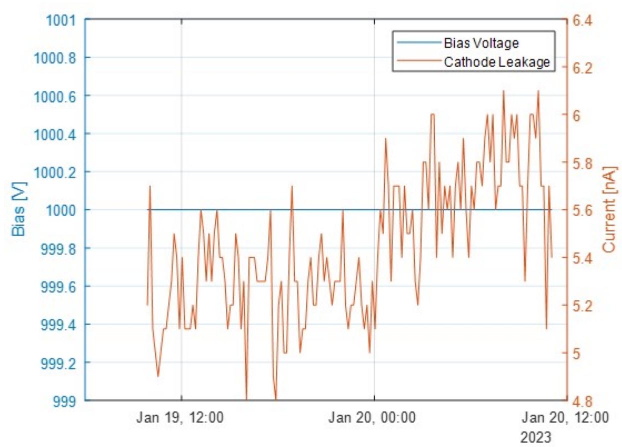


Figure 20: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137, Leakage current vs time

5.2.5 Temperature behavior

168CS2(R), 6x6, 1.7 mm pixel pitch, 1 cm thick pixel side bonded with silver. @-1000V 20, 30, 40, 20, 10, 0, 10, 20, 30, 40, 30°C. By an accident data from the measurement at 30°C right after the 40°C as deleted, so for this first set of measurements it is missing. The compilation of the resolution on the best pixel spectrum, given that it was observed that the overall resolution got much more affected by the in crease of temperature, and the peak centroid is summarized to observe the difference.

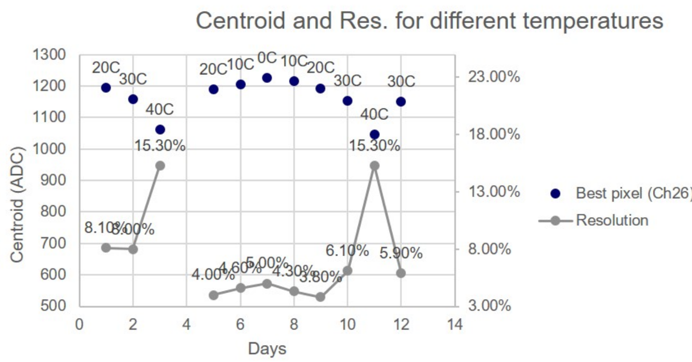


Figure 21: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at different temperatures, peak centroid and resolution

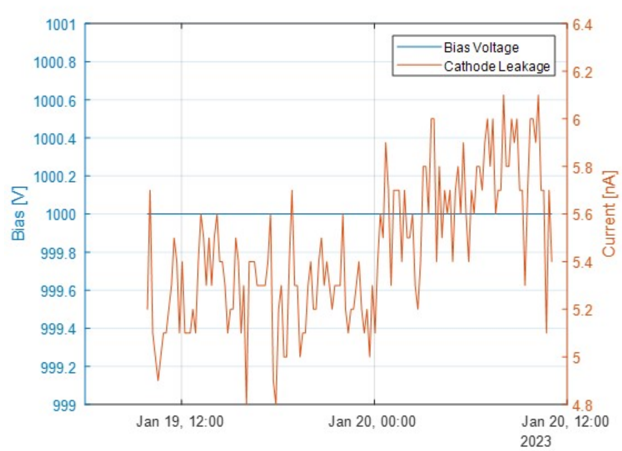
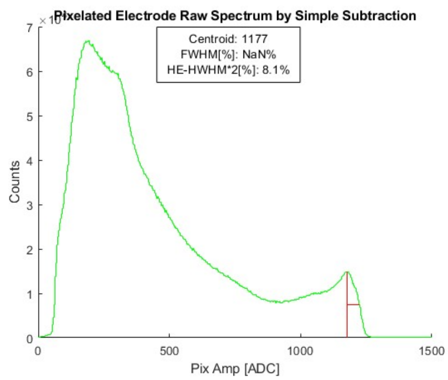


Figure 22: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 in different temperatures, Leakage current vs Temperature

We can observe that the centroid varies around 1200ADC +/- 100 for all the temperatures in between 0 and 30°C, shifting back (decreasing with the temperature increase) but for 40°C it doubles the deviation, same with the resolution that is good and acceptable until 40°C. That evidences a correlation non linear behavior different then observed in CZT, according conversations with Sara Abraham that develops some studies around the temperature behavior of CZT. So, for better investigation, another round of measurements is made at the same high voltage but only for temperature from 20°C to 40°C and back to 20°C in increments of 10°C, and plots of the general spectrum, spectrum of the best pixel, depth curve and drift duration vs C/A (Cathode/Anode) ratio, this last one to observe the regularity of the electric field in the material. This last plot was also processed with the data before however the settings (Sample Hold specifically) cut off the plot for the highest drift duration values.



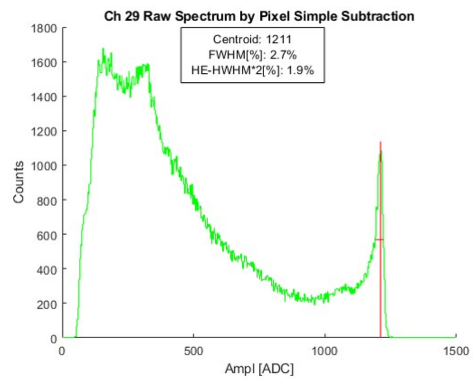


Figure 23: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 20°C, overall spectrum and best pixel spectrum

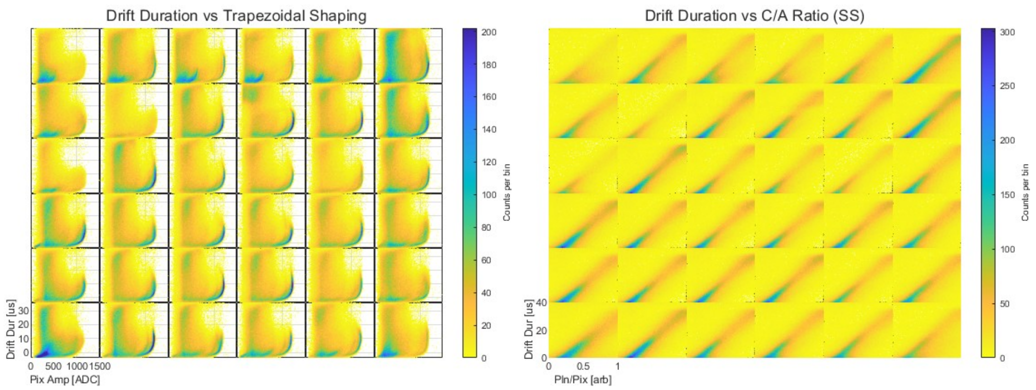


Figure 24: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 20°C, depth curve and drift duration vs C/A ratio

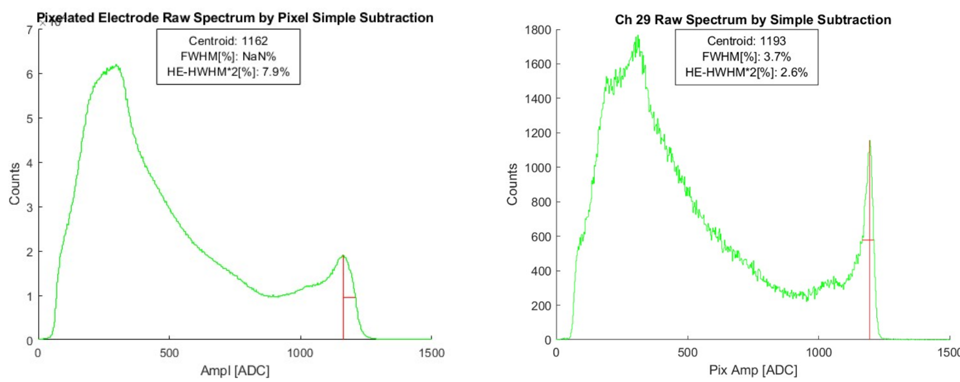


Figure 25: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 30°C, overall spectrum and best pixel spectrum

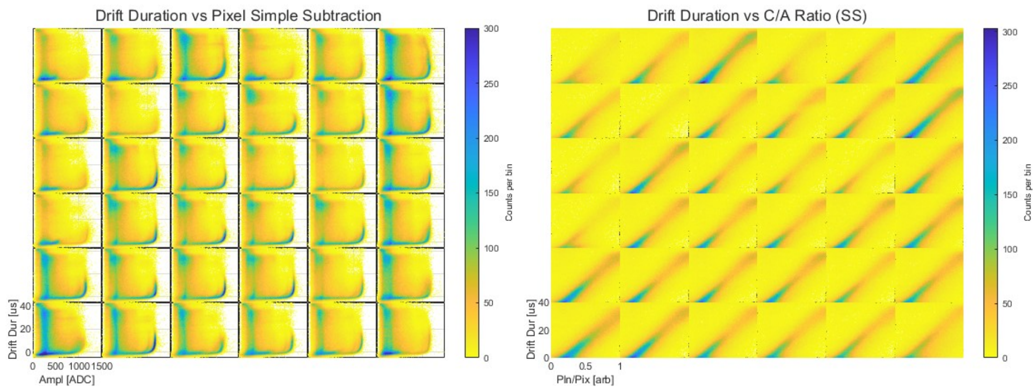


Figure 26: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 30°C, depth curve and drift duration vs C/A ratio

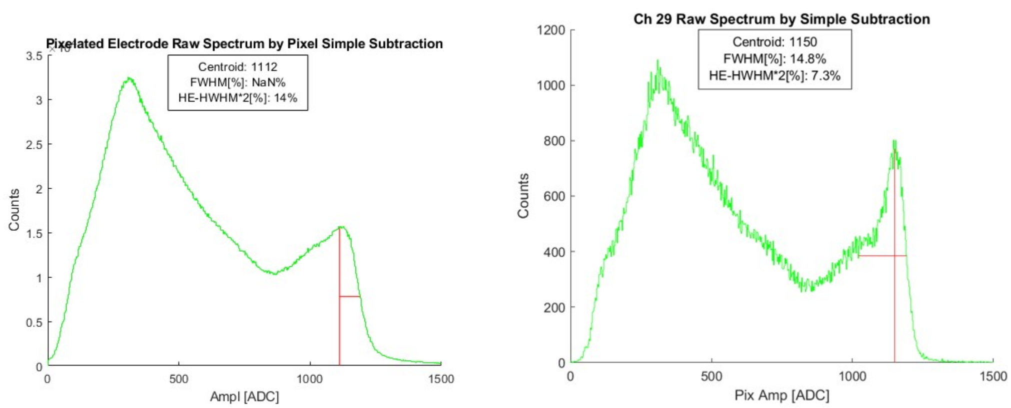


Figure 27: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 40°C, overall spectrum and best pixel spectrum

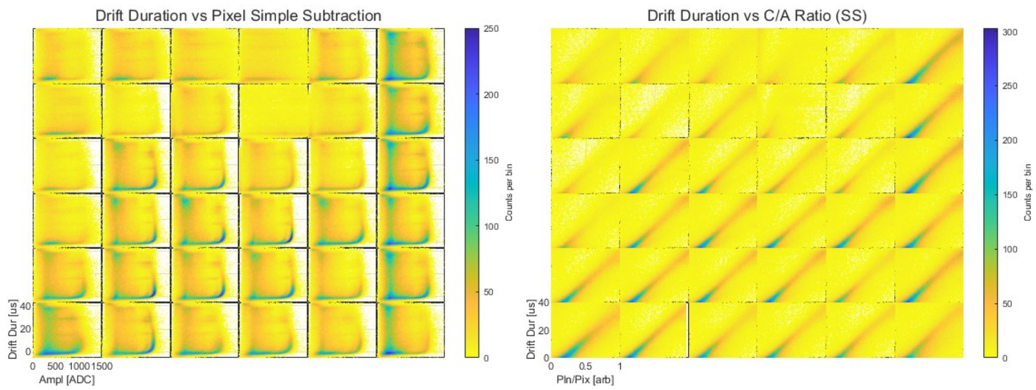


Figure 28: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 40°C, depth curve and drift duration vs C/A ratio

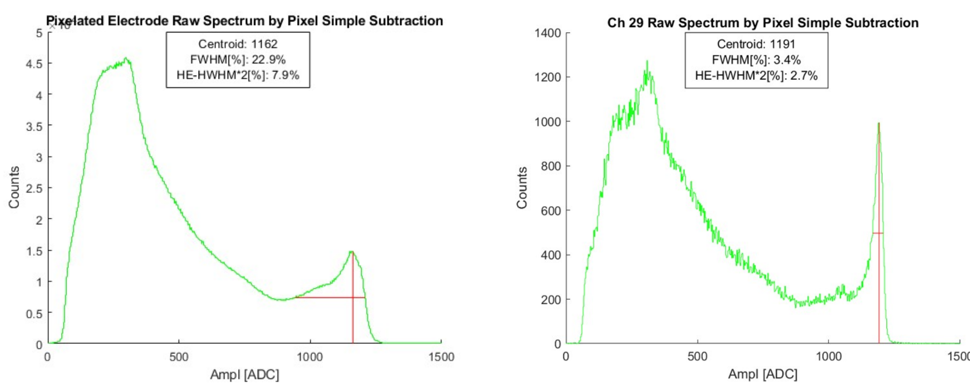


Figure 29: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 30°C, overall spectrum and best pixel spectrum

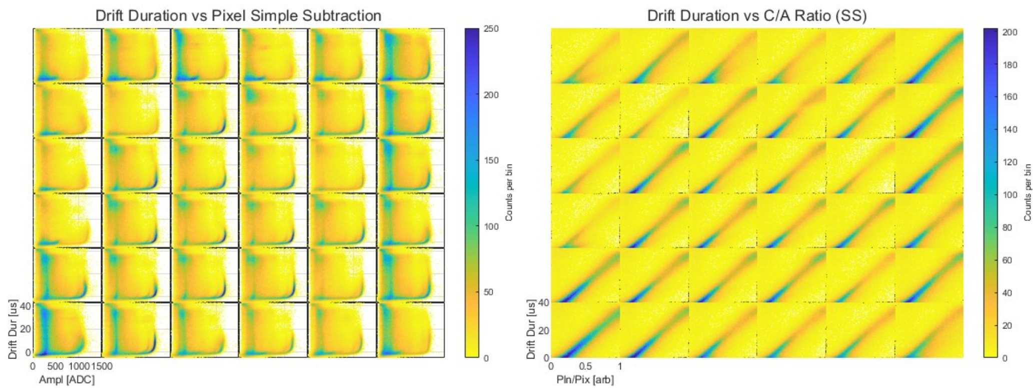


Figure 30: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 30°C, depth curve and drift duration vs C/A ratio

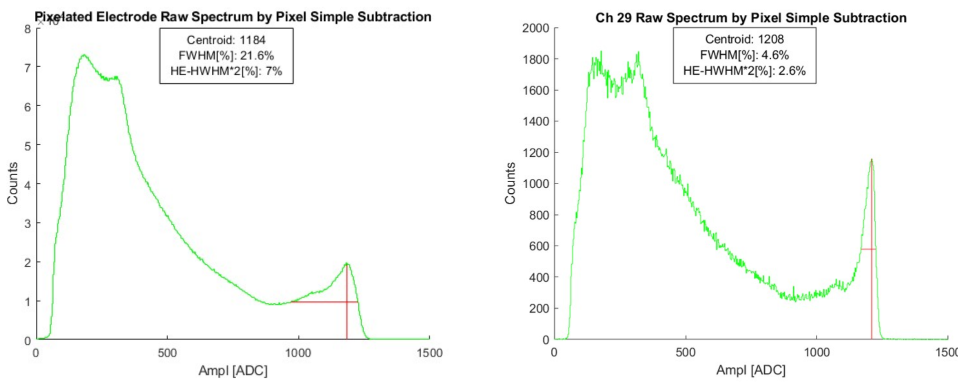


Figure 31: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 20°C, overall spectrum and best pixel spectrum

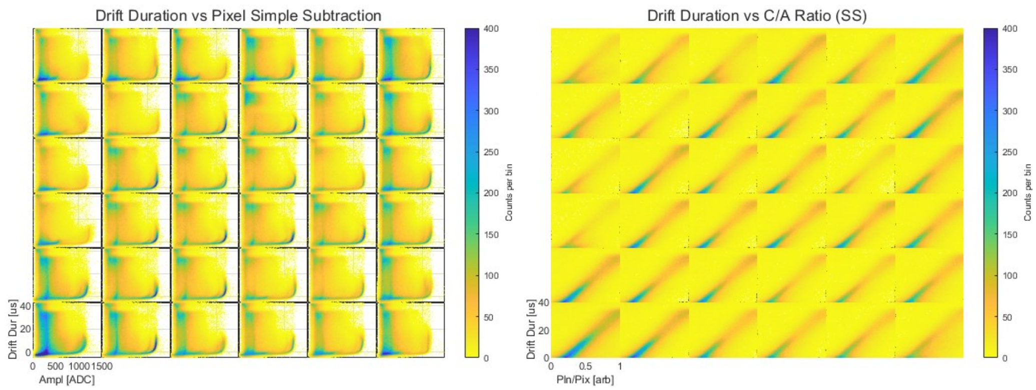


Figure 32: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 20°C, depth curve and drift duration vs C/A ratio

The compilation in this case, that confirms and repeat the first results with a bit of improvement can be seen below.

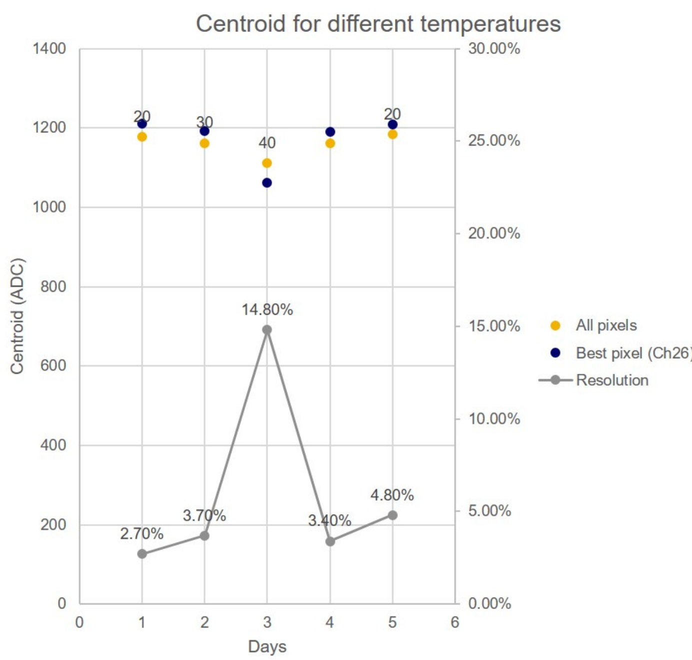


Figure 33: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 in different temperatures, peak centroid and resolution - 2nd round

In order to investigate if the behavior is consistent ant to the material regardless the crystal manufacture, size and finishing, the same set of measurements were made with the crystal 212AB2 (11x11, 1.72mm pixel pitch, 1cm thick, pixel side bonded with carbon) at HV of -1000V in temperatures of 20°C, 30°C, 40°C, 30°C, 20°C. Notice that this second crystal has a distinct bonding material for the cathode side what can help to see if any impurities drifted from the bonding material could be affecting the results.

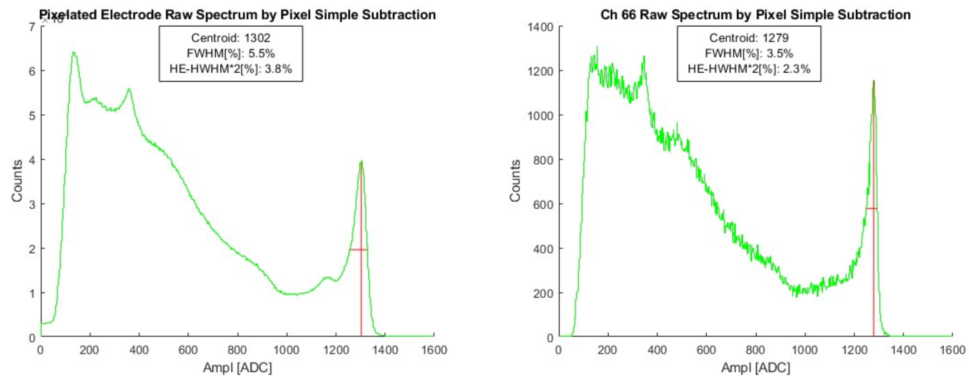


Figure 34: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 20°C, overall spectrum and best pixel spectrum

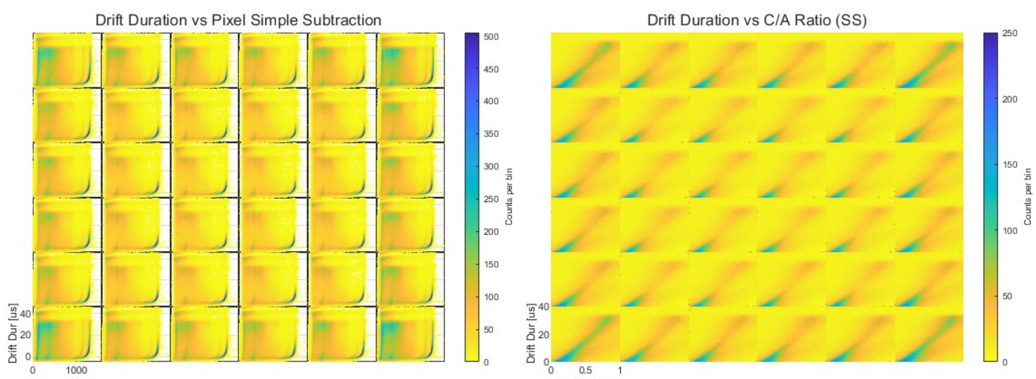


Figure 35: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 20°C, depth curve and drift duration vs C/A ratio

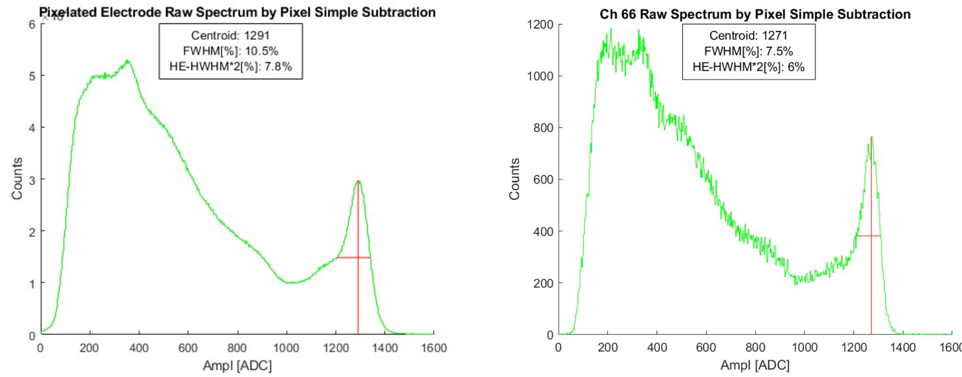


Figure 36: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 30°C, overall spectrum and best pixel spectrum

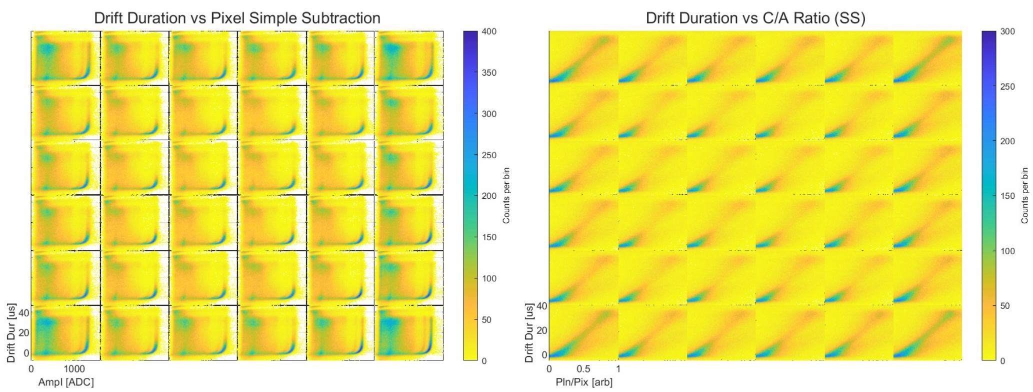


Figure 37: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 30°C, depth curve and drift duration vs C/A ratio

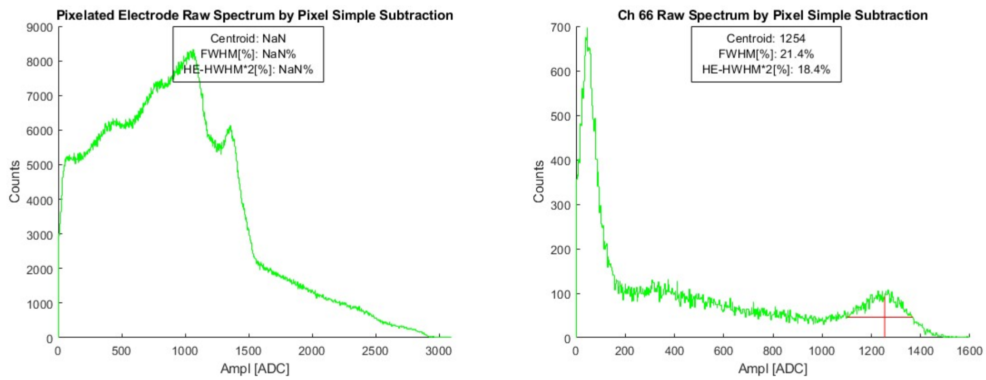


Figure 38: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 40°C, overall spectrum and best pixel spectrum

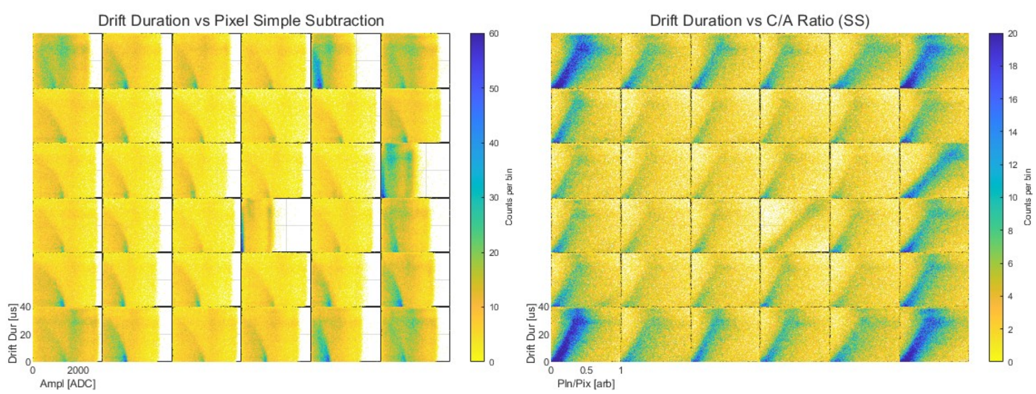


Figure 39: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 40°C, depth curve and drift duration vs C/A ratio

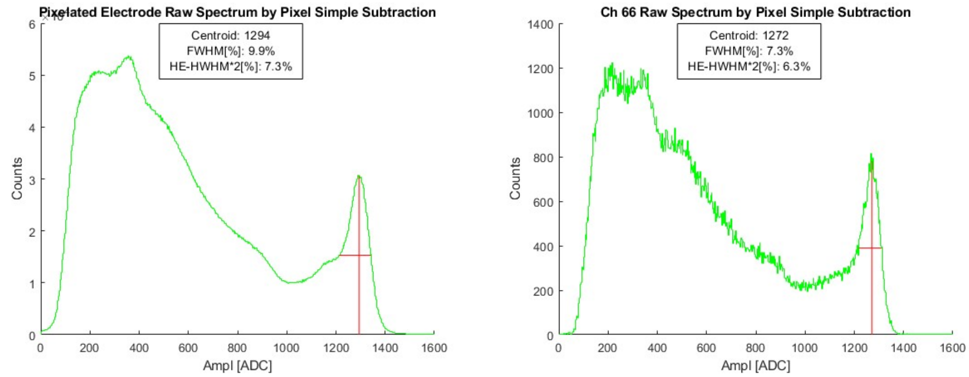


Figure 40: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 30°C, overall spectrum and best pixel spectrum

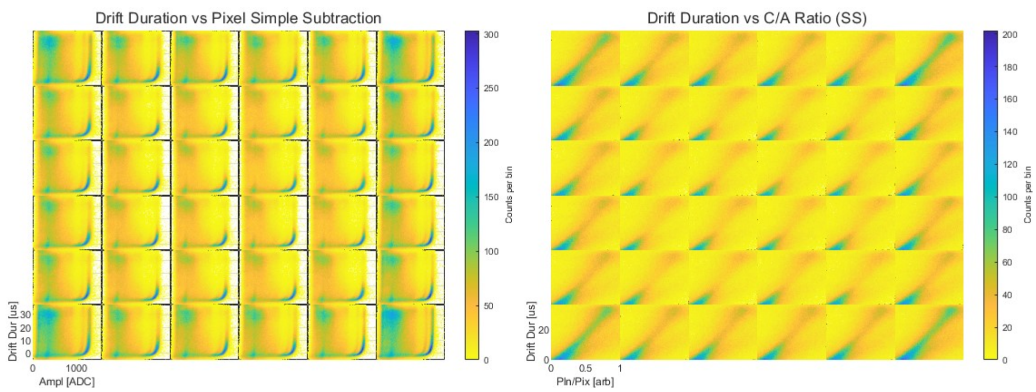


Figure 41: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 30°C, depth curve and drift duration vs C/A ratio

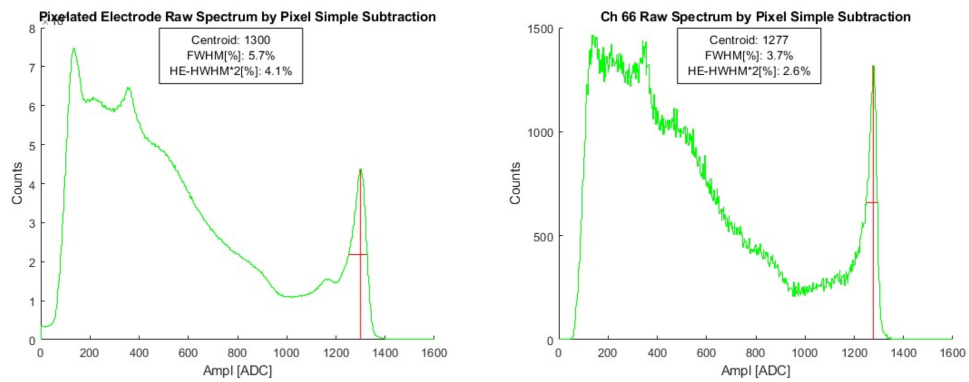


Figure 42: 212AB2 at HV=-1000V around 24h exposed to Cs-137 at 20°C, overall spectrum and best pixel spectrum

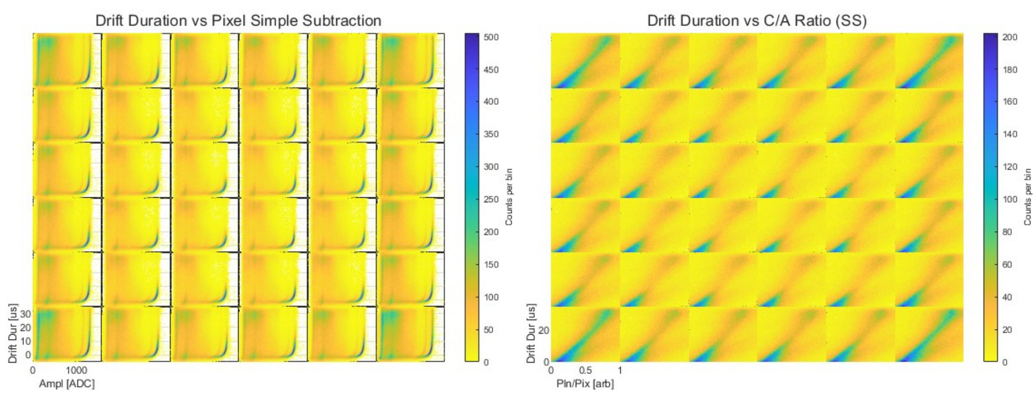


Figure 43: 168CS2(R) at HV=-1000V around 24h exposed to Cs-137 at 20°C, depth curve and drift duration vs C/A ratio

The summarize on resolution and peak centroid for the 212AB2 crystal:

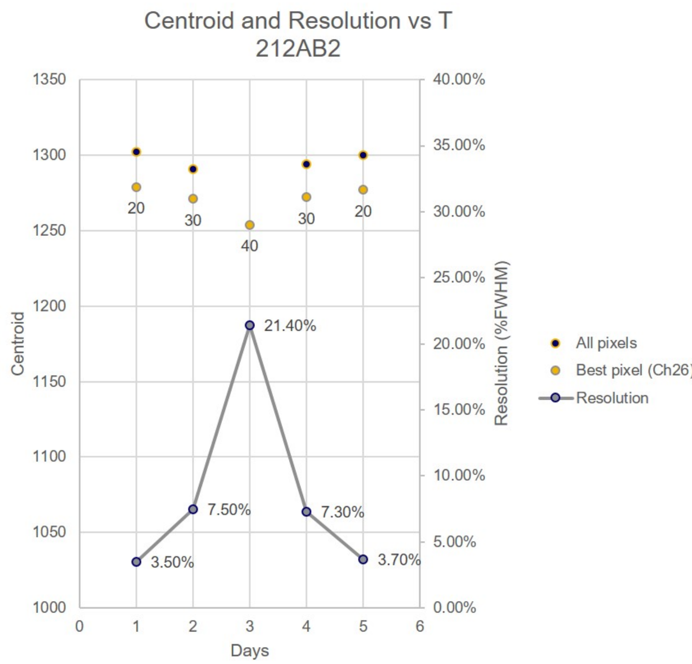


Figure 44: 212AB2 at HV=-1000V around 24h exposed to Cs-137 in different temperatures, peak centroid and resolution

Comparing both crystals, looking at figures 33 and 44, we can notice that the increment of resolution happens in both but the average for the 212AB2 crystal is worse than 168CS2(R), also that variance of the peak centroid is stronger for 212AB2.

6 Discussion and Results

The results and plots on the drift duration vs C/A ratio intended to analyse the electric field. And as so, the electric field was found linear in most of cases with wider or more narrow lines and some fading. Besides for the 212AB2 at 40°C where it does seem that the interactions on the crystal were not well caught by the electronics or maybe cutoff by some of the settings and the spectra and all the plots are collapsed.

Concerning the temperature behavior, what happens at 40°C is repeated in all the cases, the lack of distinguishable peaks, easy to observe at the depth curve, where for 168CS2(R) you can observe at the pixels on the top (lines 4/8 and 5/7 of channel map) on figure 28, that the spectra collapse, even though the other pixels are still able to count events and form some peak. On the other hand for 212AB2 at the same temperature it seems to happen all over the channel/pixels. The collapsing as observed with 168CS2(R), happening in some pixels but not in all, could suggest whether a material phenomena correlated to the edge or the electronics of those pixels. Definitely more analysis and other data in different settings could help investigating the malfunctioning and the source of the problem or moreover the correlation with the temperature. Giving a better look on the same pixel among the ones affected by the increase of temperature like the channel/pixel 47 and comparing an amount of 50 waveform events at both 30°C and 40°C and presented here, we can observe some electronics occurrences:

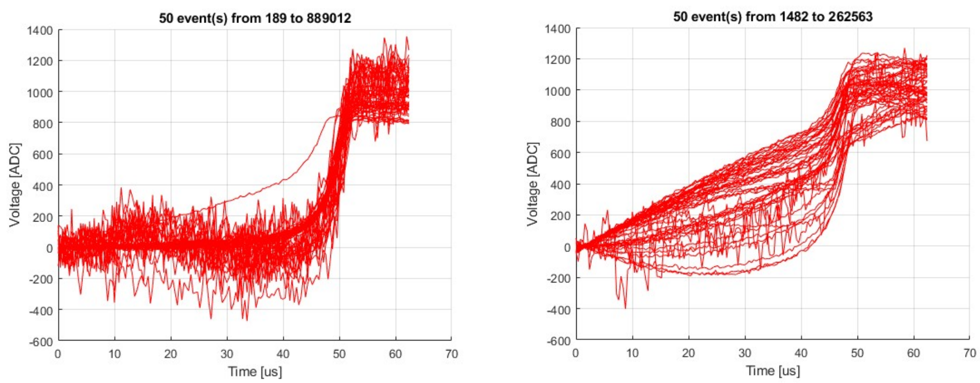


Figure 45: 168CS2(R) ch.47 anode waveforms at 30°C(left) and 40°C(right)

Note that there is a lot of noise, both high frequency related to the ASIC that seems to be the same for both cases but mainly at 40°C a huge variance above and below 0 voltage is observed and we can barely see the rising signal of the waveforms, while at 30°C you can see the rising signal and a clearer voltage gradient but also can observe a very oscillated baseline. To observe this last feature in other pixel where we can still see some peak under both temperatures, ch.101 anode and cathode waveforms were plot.

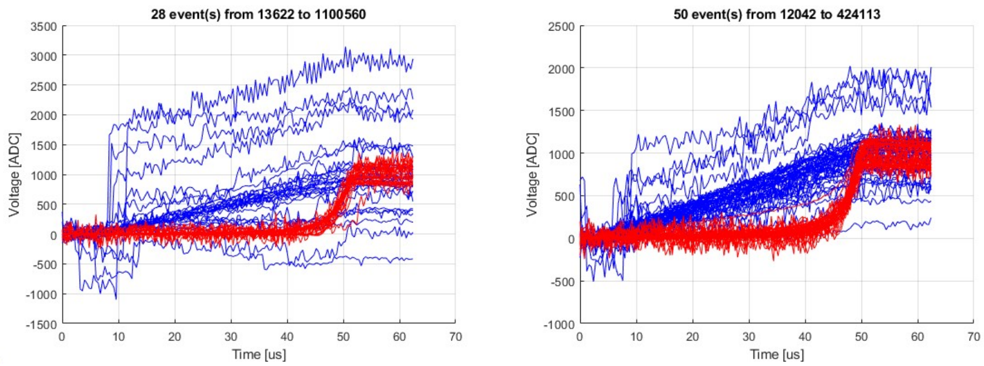


Figure 46: 168CS2(R) ch.101 anode waveforms at 30°C(left) and 40°C(right)

On these plots you can definitely perceive the low frequency noise, stronger at 40°C. This kind of noise is related to the leakage that for the 40°C measurement was around 45nA while the 30°C around 15nA what makes sense to justify the greater impact of this noise.

With this observed I tend to say that the electronic noise still makes it too difficult to perform detection at this temperature. When compared to the use of the same ASIC but with CZT, the temperature didn't affected so drastically the resolution however the leakage for CZT in an order of 25 times the one for TlBr, according information discussed in the monthly meetings and at the lab. With that consider, the electronics shouldn‘t be the problem unless we notice that the time space in which the waveforms for CZT happen is in the order of 4 μ s, whereas in my case is of 60 μ s that is expected due to the slower mobility of carriers in TlBr than in CZT. That could justify why this electronic low frequency noise didn't impacted measurements with TlBr and actually does with TlBr.

The electronics adjustment wouldn't exclude the material manifesting issues. The carrier mobility can still be so affected by the temperature [8] that it would the time shaping a remainder obstacle for measuring and detecting.

7 Conclusions and Future works

The experience of setting up, collecting data, reviewing the signal processing and the data processing of the measurements gave me much more understanding on:

- how the electronics of a radiation detector works and some of the components and their role on the signal processing with the capability of correlating the components that could possibly change some feature
- the relation of the data collected and the necessary processing to give effective information about the radiation source and its specific energy
- the operation of the hardware and software used as well as some of the various possible settings and how they can constrain or support your analysis
- TlBr material, its properties and phenomena that happen inside it correlated to radiation energy collection and electrical carrying/.transmitting
- a number of other knowledge that I can develop about the subject

One conclusion for sure is that half an year is just the necessary to learn how to start investigating, collecting and processing helpful data pertinent to the research, so as a dedicated study and research I could absolutely learn some concepts and get some knowledge on how to start a project.

Decent results regarding resolution were found under room temperature, like 1.79% with 212AB1 crystal in the H3DD s-series device, that supports the possibility to use CZT alike system for TlBr limited to room temperature or colder.

Taking the case study about the notable and not linear decrease of resolution under some few degrees over room temperature was a challenging and rich experience. For the same time it would frame apparent simple parameters like resolution, peak centroid and temperature, the correlation of all is consequence of other various dynamics inside the crystal and the circuit, and it was found that a lot of assumed settings could affect or enrich the data and its following analysis. For instance, the sample-hold setting that was changed to not cutoff the longer drift signals, ended up to cut some cathode side signals because another adjust should have on the miscellaneous settings

As far as this study went, the low frequency noise is still in the way of completely see what is happening in the crystal or which other possibilities could be tried with the signal processing. Obtaining a more stable baseline on the waveforms under high temperatures could be a good start and one suggestion for a future follow up study.

Another suggestion could be adapting an circuit for the long shaping time and to diminish the current leakage or the low frequency noise and that would be useful for keep seeing the different phenomena caused by the crystal at high temperature.

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