MEMORIA DE PRÁCTICAS EXTERNAS

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1. Introduction: Laser plasma nuclear physics.

Nuclear plasma laser physics is a field of study that focuses on the use of high-intensity lasers to generate and control extremely hot and dense plasmas. These plasmas are used to study properties of nuclear particles and nuclear decays. A high-power laser is employed to generate an extremely intense and short light pulse. When this laser pulse interacts with a target, it creates a plasma by heating and ionizing the target material. Once the plasma is created, as some nucleus has been excited, nuclear decays can be studied by observing the particles emitted during the decay process.

1.1 Excitation of the 181Ta and x-flash issue.

In our case, through the use of the laser, it is intended to study the nuclear disintegration of the 181Ta (Tantalum 181). This nucleus has a half-life time of 6.05µs and the energy of the radiation which emits is of 6.2KeV.
In order to be able to carry out its study, as already mentioned, a high-power laser beam is used with the objective of excite the nuclei and obtaining so 181Ta. In order to study the radiation emitted by this nucleus, detectors are used (explained in more detail in the set-up section). However, during the laser shot, these detectors are stunned by the amount of signal they receive and therefore, for a certain period of time, they are not useful to measure. In addition, also with the aim of studying the radiations emitted by the 181Ta, in the experimental set-up is intended to make use of an amplifier. Nevertheless, the high power of the signal captured during the laser shot would damage this device. For solving these issues, the signal is captured using two detectors (APDs) and doing the subtraction of the two signals captured. Of this way, we would be able to start taking measures earlier and the maximum of the final signal captured would be lower.

1.2 The internship objective.

The internship had the aim of studying the signals taken by the detectors placed in the experimental set-up presented in the next section. During this experience, there have not been a nucleus excitation, and therefore, the study of the nuclear decay of the 181Ta has not been realised. However, by studying these signals, some conclusions of importance for the future study of the nuclear decay will be presented.
The study of these signals was conducted in Python.

2. Experimental set-up.

The following picture shows the experimental set-up used:

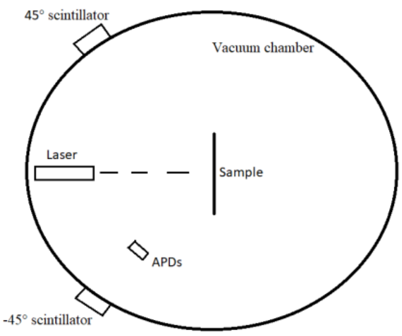


Figure 1: Experimental set-up.

The experience took place in a vacuum chamber, where it is placed the laser, the sample and the APDs (Avalanche Photodiode Detectors) places at -45°. Situated in the exterior of this chamber, there are two scintillators, the first is place at 45°, and the other one at -45°.

2.1 The laser.

The laser used has a higher power of $10^{16} W/cm^2$ and long impulsions: some microseconds. Firing against the sample, it produces this generation of the 181Ta.
The experimental data set we have is the following: for each shots of the laser (called with a number), it has been registered the signal of each of the two LaBr3 as well as the signal of the APD(s).

2.2 LaBr3 scintillator detector.

The two detectors situated outside the vacuum chamber are Lanthanum bromide ($LaBr_3$) scintillators. They work as follows. When ionizing radiation, such as a gamma ray, hits the LaBr3 crystal, Compton effect takes place: it is emitted one electron and light. This light arrives then to a photoelectrode, where thanks to photoelectric effect, one electron is emitted and by employing a multiplier it is possible to generate a current of a multitude of electrons. That current is what we are able to measure. However, not all the energy that arrives is transformed always into light (due to the electron emitted in the Compton effect). Therefore, the energy we measure is not normally equally to the energy that has the radiation.
In the following picture it is shown an example of three different signals of both scintillators after three different laser shots. It has been obtained coding a Python program (More information about the Python program developed during the internship will be presented later in the section 3.):

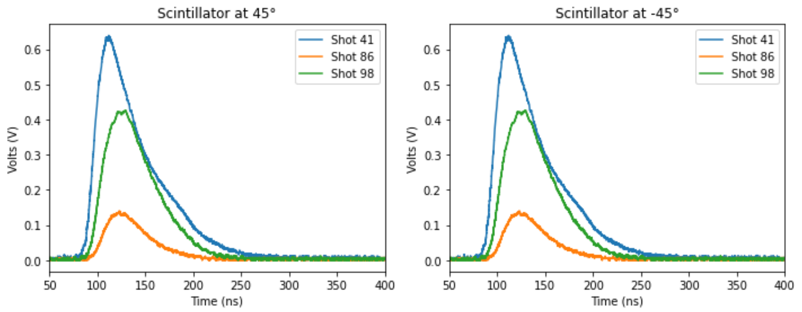


Figure 2: Signal of both scintillators.

2.3 Avalanche Photodiode detectors (APDs).

Two APDs are placed inside the vacuum chamber at -45°.
These detectors are made of silicon, so they are not conductive. However, by applying an electric champ, the silicon becomes a conductive material if the temperature is high enough (room temperature). Therefore, when the radiation reaches the silicon in which we are applying an electric field, electron-hole pairs are created. The electron advances through the atoms to a multiplier. On the contrary, the hole produced by the absence of the electron that is advancing moves in opposite direction. Once the electron arrives to the amplifier this produces a current of about 100^3 electrons.
APDs are useful if the energy of the radiation they are capturing is not too high, because, in that case, the radiation would go through the silicon part without releasing an electron. In our case, they are useful, because they are able to measure the gamma radiation emitted by the 181Ta, as it was said, it has an energy of 6.2KeV.
These detectors have the following experimental electronic set-up:

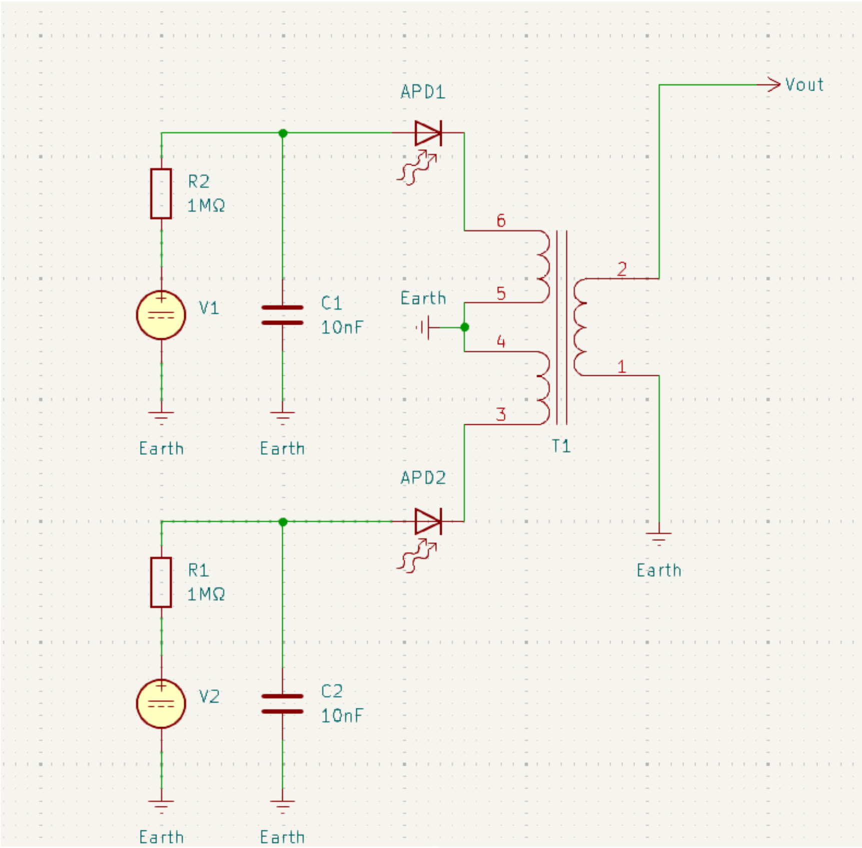


Figure 3: *Experimental electronic set-up of the APDs.*

If both APDs are polarised, then the signal we obtain with these electronic circuit is the subtraction of the signals taken by both APDs. However, if only one APD is polarised, then the final output is the signal taken by only one APD.
In the following picture, as it was done for both scintillators, it is ploted the signals of one APD after three laser shots:

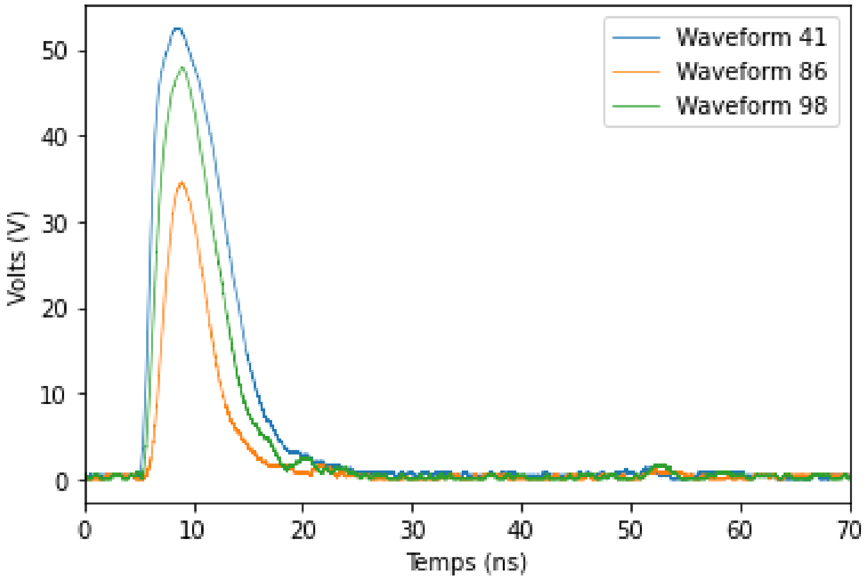


Figure 3: *One APD signals plots.*

And in the following picture it is shown three subtracted signals, that is, having both APDs polarised.

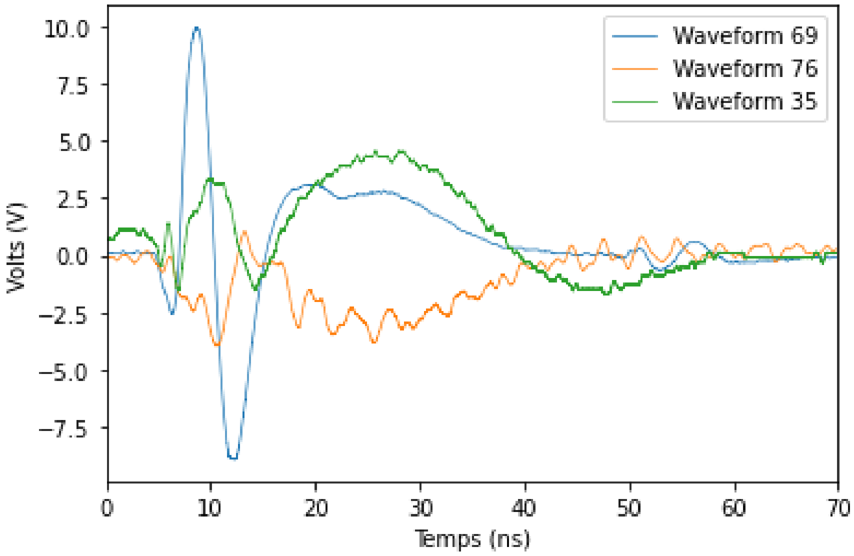


Figure 4: Subtracted signals plots.

In the data set, the signals have been taken using different APDs whose names are: APD34, APD36, APD37 and APD38.

2.4 Study of the signals taken by both LaBr3: Energy display.

In this section it will be proved that the signal, after colliding with the sample, it moves isotopically through space.

For proving that isotropy of the signals energy, we have computed as follows. For each of the signals of the data set of the 45° Labr3 and for the signals of the -45° LaBr3, the area of the signal has been calculated. Then, plotting the areas of the signals of the -45° LaBr3 in function of the areas of the 45° LaBr3 we have obtained:

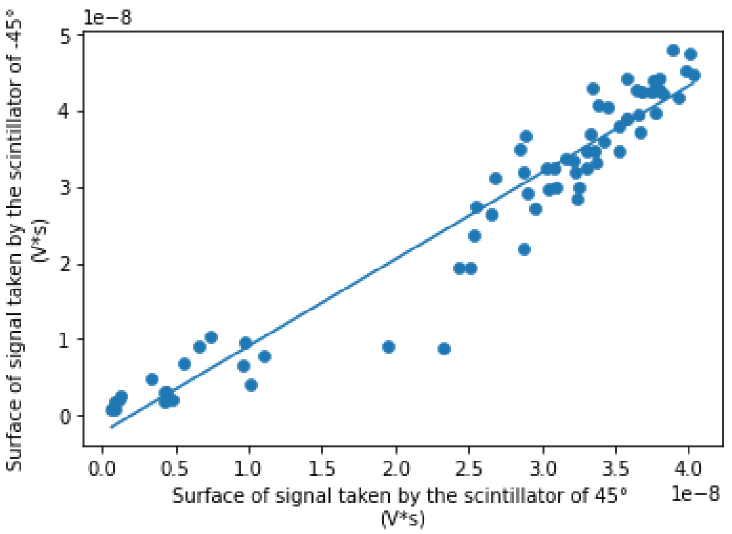


Figure 5: For each of the shots it is plotted the surface of the signal of the scintillator of -45°(CH5) in fonction of the signal of the scintillator of 45° (CH4).

The value of the slope is: b =1.13844192 and the intercept is: a = -2.26934899e-09 Vs

The mean squared error = 1.5714328269099426e-17

The root mean squared error = 3.96413020334845e-09

Conclusion: As the slope of the line regression has a value very closed to 1, it can be concluded that, after the collision of the laser shot with the sample, the signal moves isotopically through space. This is important to know, as even though, both APDs are closely positioned relative to each other, if the energy signal would move more intensive in one direction, the subtraction would not be so efficient.

2.5 Shot map: APD/laBr3

In this section we have only considered the signals using only one APD polarised. For each of those signals, it was computed the area of the signal of the APD as well as the area of the signals of the -45° scintillator. Then, it was plotted the surface of the signal of the APD in function of the area of the signal of the -45° scintillator:

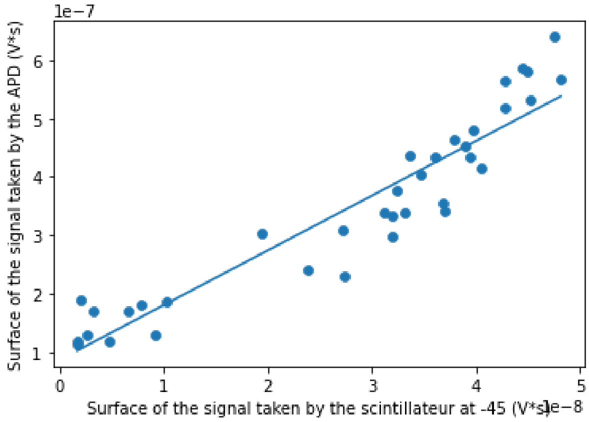


Figure 6: For each of the shots it is plotted the surface of the signal of the APD in function of the signal of the -45° scintillator (CH5).

And plotting the area of the signals of the APD in function of the signal of the 45° scintillator:

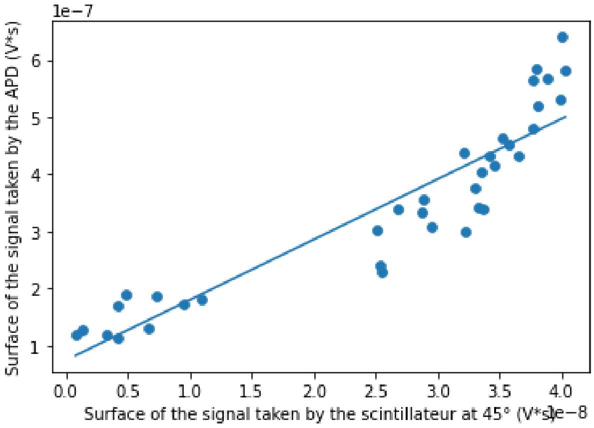


Figure 7: For each of the shots it is plotted the surface of the signal of the APD in function of the signal of the 45° scintillator (CH4).

In section 4 we will continue analysing this graphic.

3. Python program.

As it has been mentioned, all the signal analysis has been conduced in Python. In this section, some information about the Python programs developed during the internship will be shown, but not every used function or the actual code will be displayed due to the extensive length it would entail.
For coding the programs, it has been used the integrated development environment Spyder, as it is specially designed for scientific computing and data analysis.
The principal libraries that have been used in these programs are:

- **Numpy**: Specialised in numerical calculation and data analysis, especially for a large volume of data.
- **Matplotlib**: Library for creating static, animated, and interactive visualizations.
- **Sklearn**: Specialised in predictive data analysis and Machine Learning.
- **Scipy**: Provides algorithms for optimization, linear algebra, integration, interpolation, signal and image processing, differential equations, statistics and other areas of science and engineering.

Furthermore, it should be noted that, in all the implemented programs, **data sets have been managed** and transformed in order to accurately generate the graphs.
Only the programs that have been relevant for obtaining conclusions will be mentioned:

- Program that reads and plots the APD(s) signals:
  For reading the signals in Python, it has been used some lines found in the following link: https://github.com/vongostev/TekWFM2/blob/main/tekwfm2/tekwfm.py It has been about 100 lines of code. The program which plots the APD(s) signal has an extension of 140 lines of code.

- Program that reads and plots both 45° LaBr3 and -45° LaBr3 scintillators signals:
  For reading the files it has been used again some lines of the python program found in Github. 112 lines of code have been used to plotting both graphics.

- Program for representing the graphic shown in the figure 5:
  For computing the integral, it has been used the function: scipy.integrate.simps(y, x) which uses the Simpson's rule. It has been considered as the integral interval: 75ns and 330ns.
  For computing the linear regression, it has been used the class "LinearRegression" from the "linear_model" module of the sklearn library.
  It is composed of 145 lines of code.

- Program for representing the graphics shown in the figures 6, 7, 8, 9 and 10:
  Again, the scipy.integrate.simps(x, y) function was used. This time, as the integral interval, it was taken [75ns, 330ns] for the scintillators signals and [4.5ns, 50ns] for the APD signal.
  It is composed of 250 lines of code.

- Program for computing the numerical subtraction. This script has a length of 150 lines of code. In section 5 it is presented more information about how it is computed and represented the numerical subtraction.

4. APD response.

In this section we have only considered the signals using only one APD polarised. In 4.1 and in 4.2 we will continue studying the figure 7.

4.1 Response of each APD.

The following graph plots the same shots as figure 6, but each colour represents a different APD. That is, the different shots have been classified according to the APD that has produced that signal.

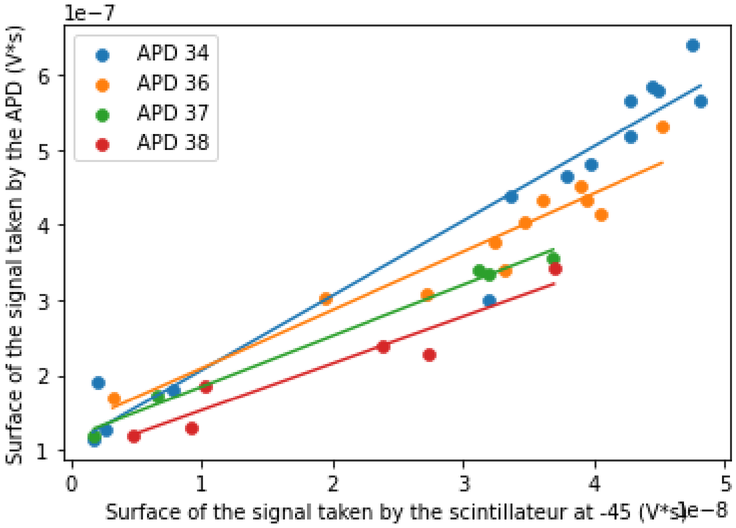


Figure 8: Same graphic as the figure 6. But each detector has been plotted in a different colour.

- For the APD34:

The value of the slope is: b = 9.95710526 and the intercept is: a = 1.06528156e-07 Vs

The mean squared error = 2.0141e-15. The root mean squared error = 4.4879e-08

- For the APD36:

The value of the slope is: b = 7.78003035 and the intercept is: a = 1.30887392e-07 Vs

The mean squared error = 7.7601e-16. The root mean squared error = 2.7857e-08

- For the APD37:

The value of the slope is: b = 6.80992707 and the intercept is: a = 1.15859403e-07 Vs

The mean squared error = 8.8089e-17. The root mean squared error = 9.3855e-09

- For the APD38:

The value of the slope is: b = 6.26671023 and the intercept is: a = 8.99396118e-08 Vs

The mean squared error = 4.7178e-16. The root mean squared error = 2.1720e-08

The following plot represents the same shots as figure 7. Again, each colour represents a different APD.

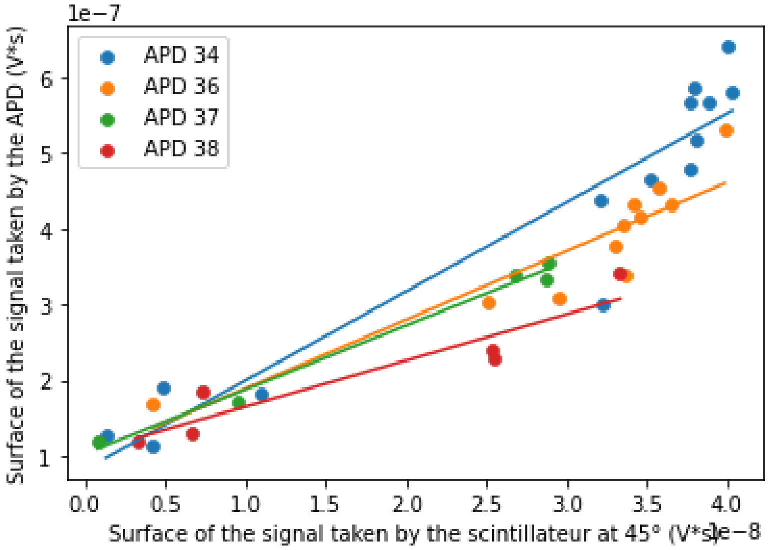


Figure 9: Same graphic as the figure 7. But each detector has been plotted in a different colour.

- For the APD34:

The value of the slope is: b = 11.76321099 and the intercept is: a = 8.18430574e-08 Vs

The mean squared error = 3.4638e-15. The root mean squared error = 5.8854e-08

- For the APD36:

The value of the slope is: b = 9.07859545 and the intercept is: a = 9.81603464e-08 Vs

The mean squared error = 1.4547e-15. The root mean squared error = 3.8141e-08

- For the APD37:

The value of the slope is: b = 8.46516649 and the intercept is: a = 1.02832591e-07 Vs

The mean squared error = 1.0961e-16. The root mean squared error = 1.0469e-08

- For the APD38:

The value of the slope is: b = 6.10446405 and the intercept is: a = 1.03870614e-07 Vs

The mean squared error = 6.9071e-16. The root mean squared error = 2.6281e-08

Conclusion: As we can see in both graphics, different lines don't coincide. We can verify this, also with the different values of the slopes and intercepts. Furthermore, the four lines are positioned identically in both graphs. The topmost line represents APD34, followed by APD36 just below it. Next it is APD37, and finally, at the bottom, we have APD38.Therefore, as each line represents the response of each APD, we can conclude that they all have different responses.

4.2 Signal shape and the relation with the energy.

The next picture represents the same shots as the figure 7. However, again, each colour represents a different APD. Moreover, the number above each point, represents the shot number. In this way, we have related the different laser shots (and therefore, the responses of the APD(s) and LaBr3 to that corresponding shot) to their position on the energy map.

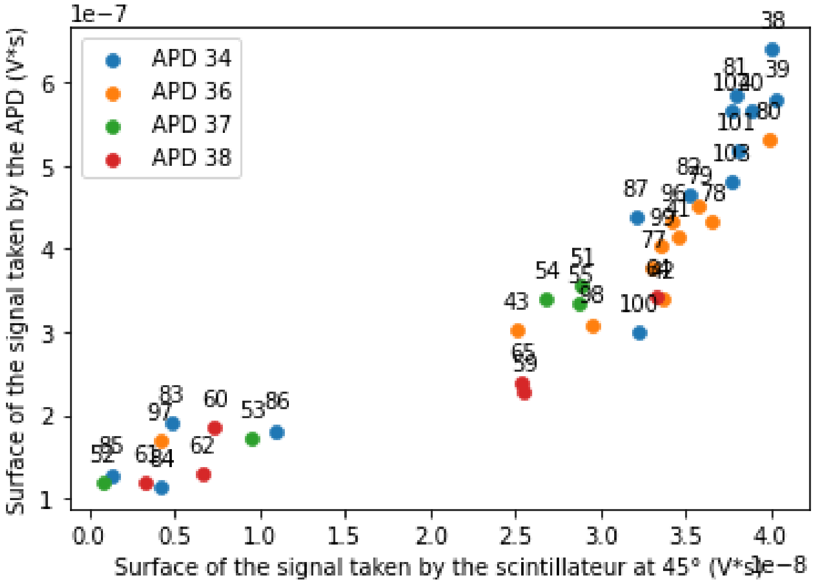


Figure 10: Map of points. Same graphic as the figure 14. Here, each shot has been identified with his number.

So as to analyse the different signals shapes in function of the energy, for each APD, it has been considered several shots with different energies and then the responses of the APD has been plotted:

- APD 34:

For the APD34 it has been considered the following shots:

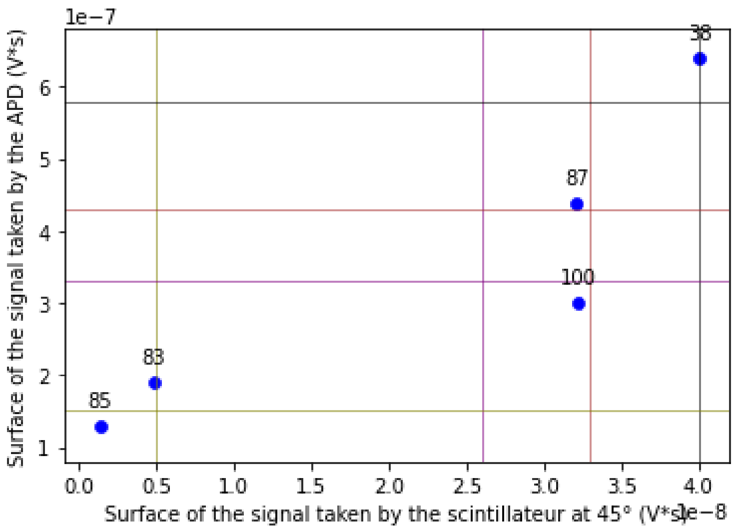


Figure 11: Shots with different energy for the APD34

And representing the APD response of these shots:

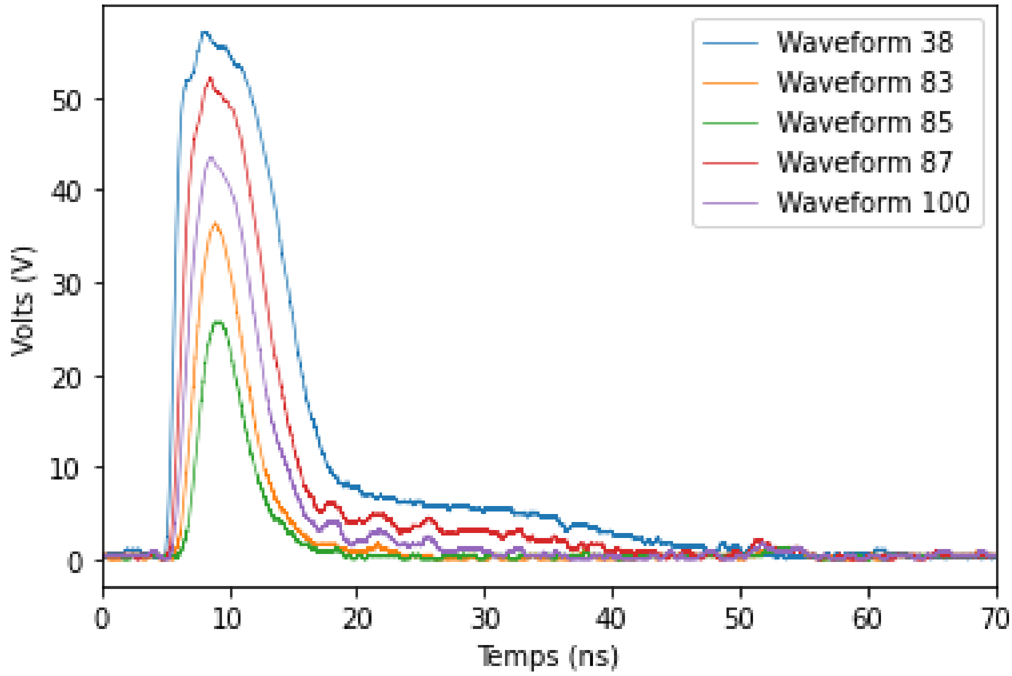


Figure 12: *APD response*

And plotting in the logarithm scale:

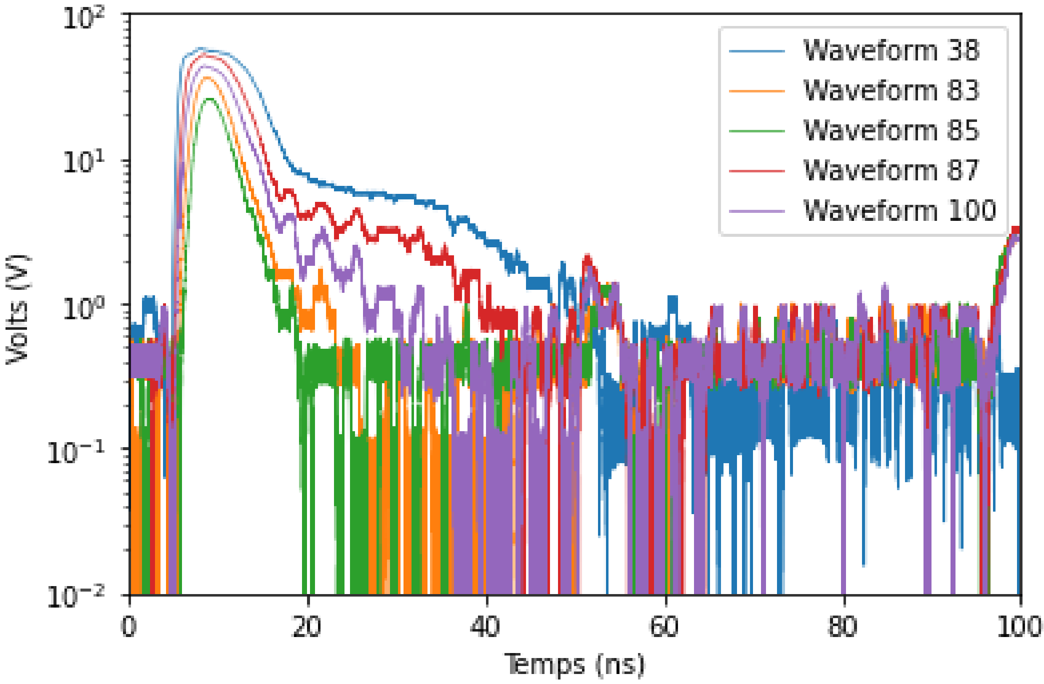


Figure 13: *APD response in logarithm scale*

- APD 36:

For the APD36 it has been considered the following shots:

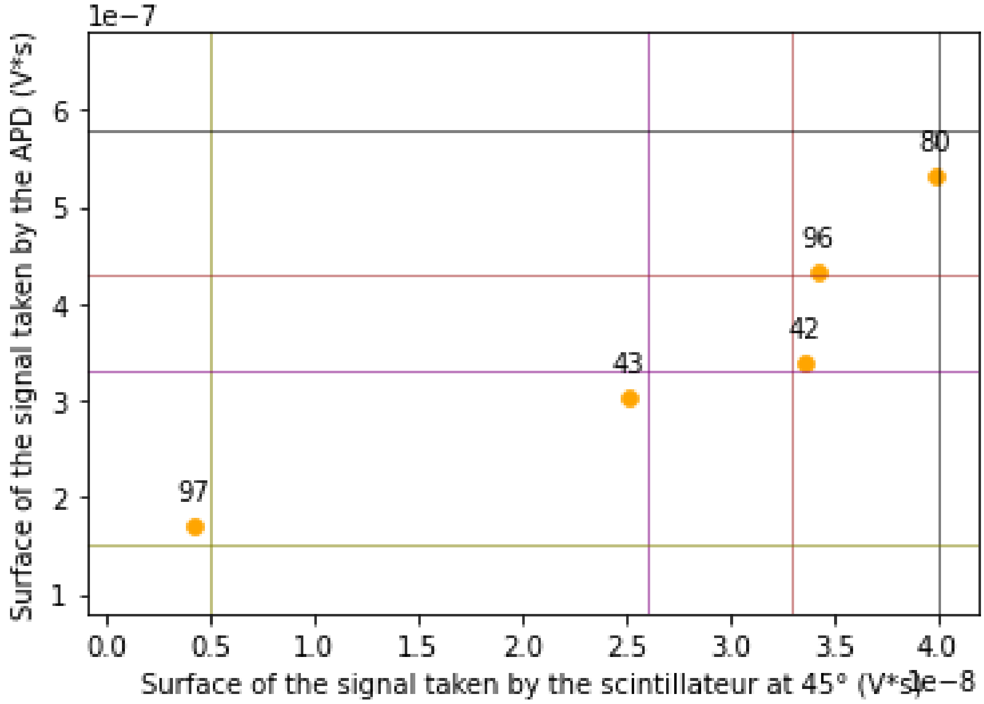


Figure 14: Shots with different energy for the APD36

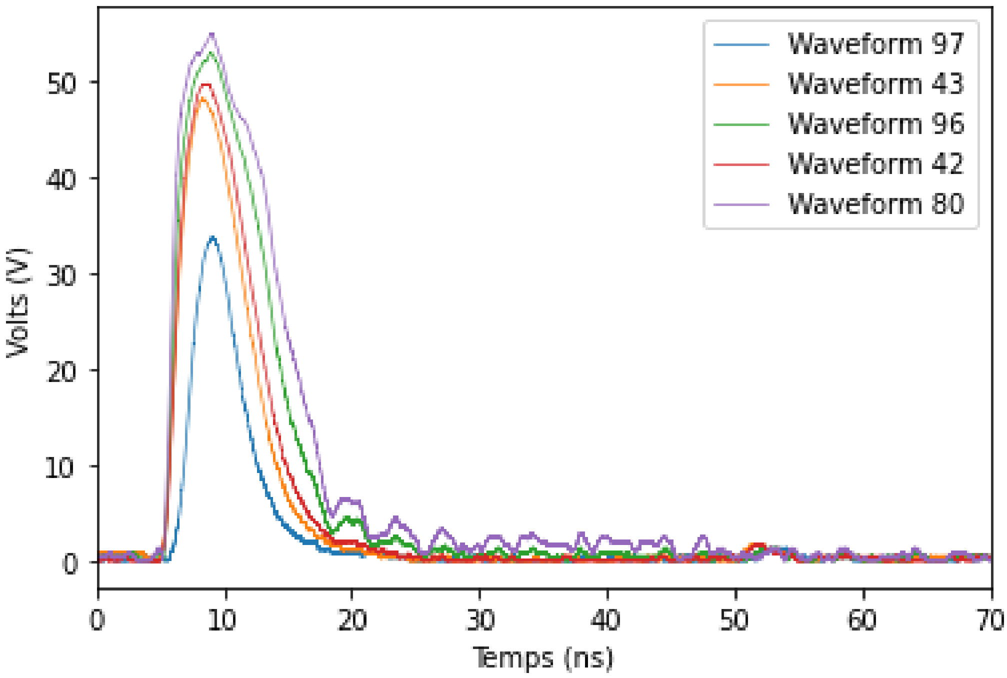


Figure 15: APD response

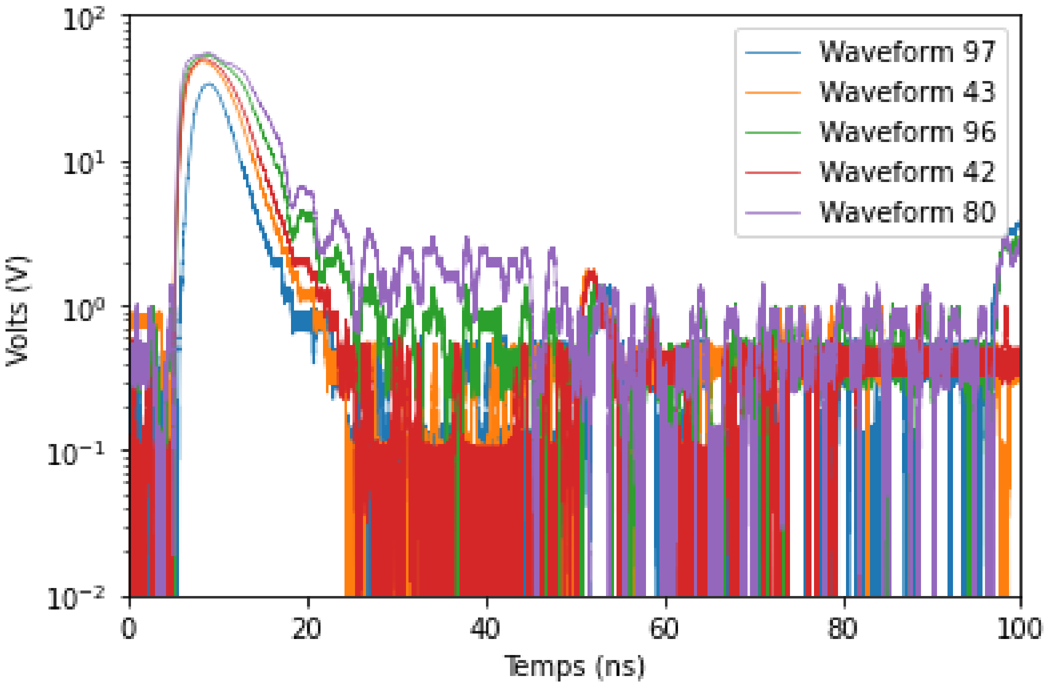


Figure 16: *APD response in logarithm scale*

- APD 37:

For the APD37 it has been considered the following shots:

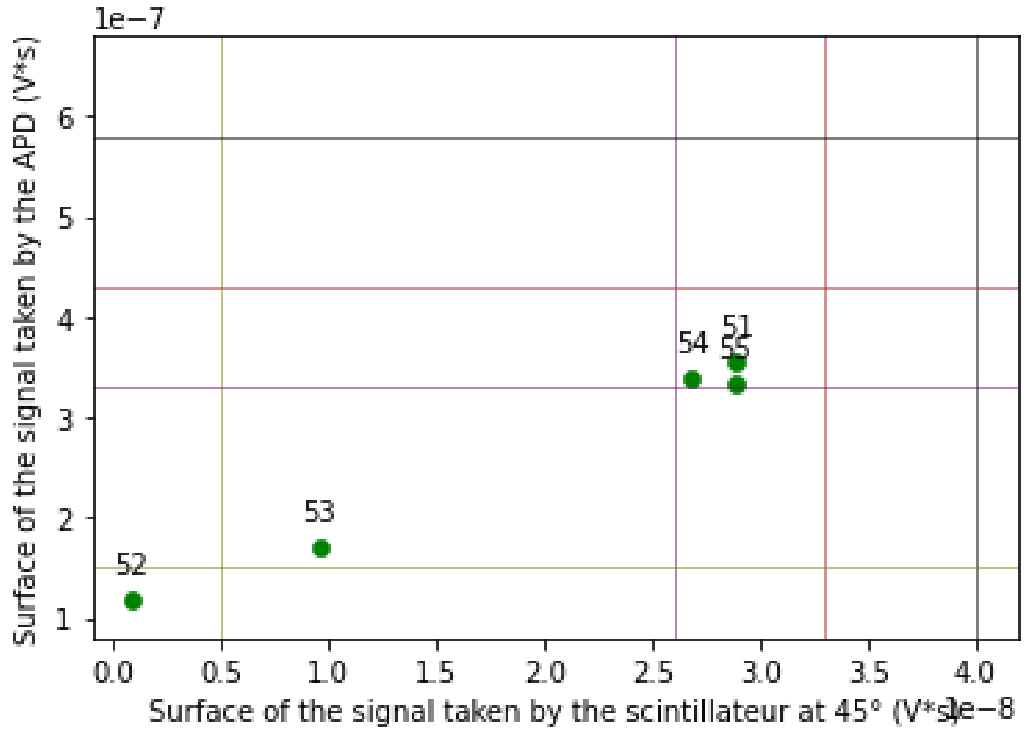


Figure 17: *Shots with different energy for the APD37*

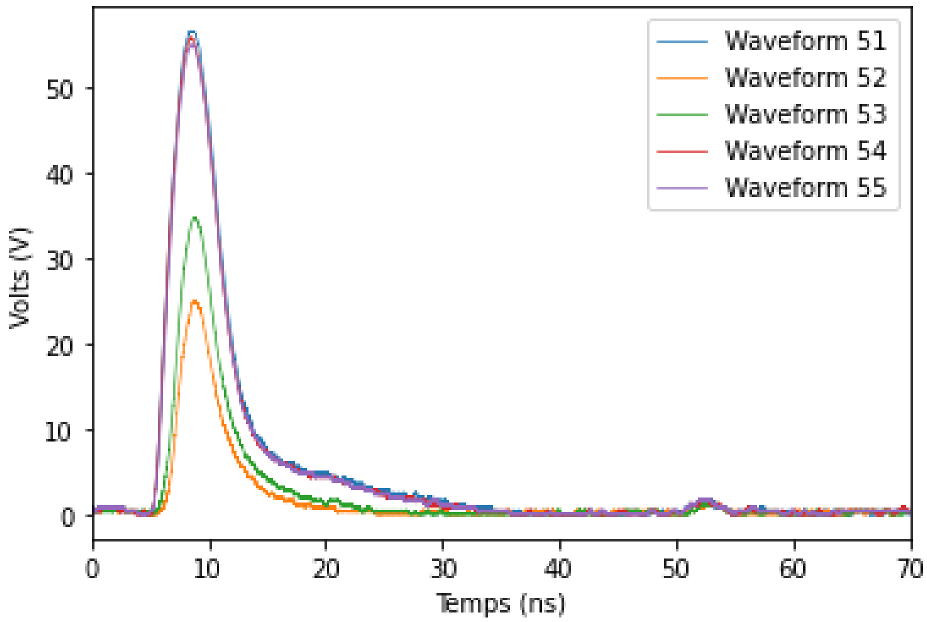


Figure 18: APD response

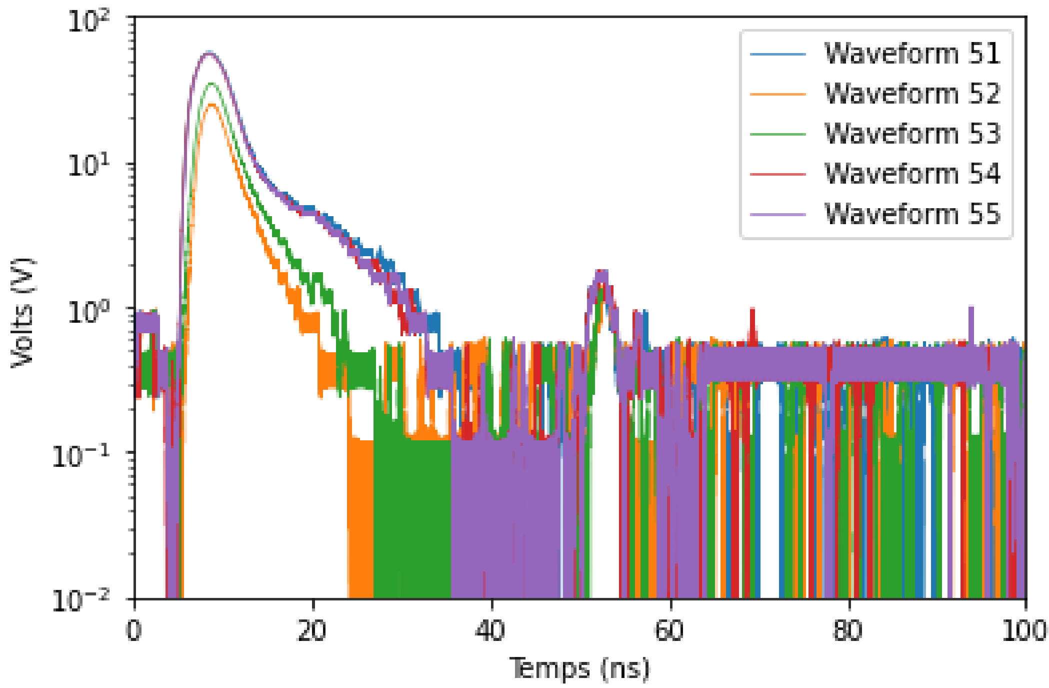


Figure 19: APD response in logarithm scale

- APD 38:

For the APD38 it has been considered the following shots:

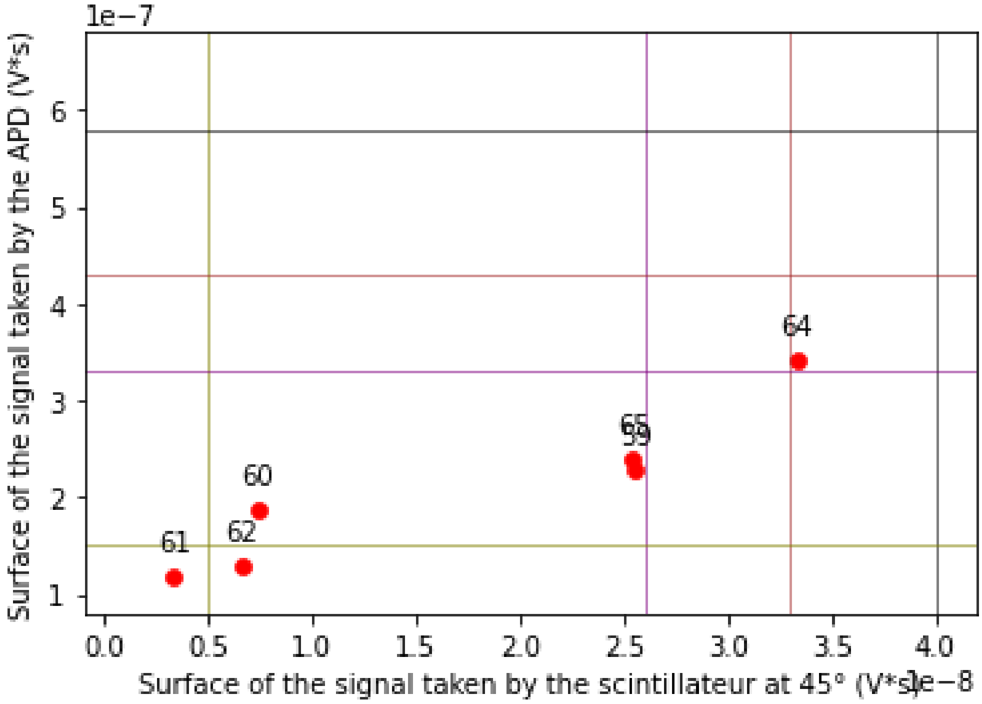
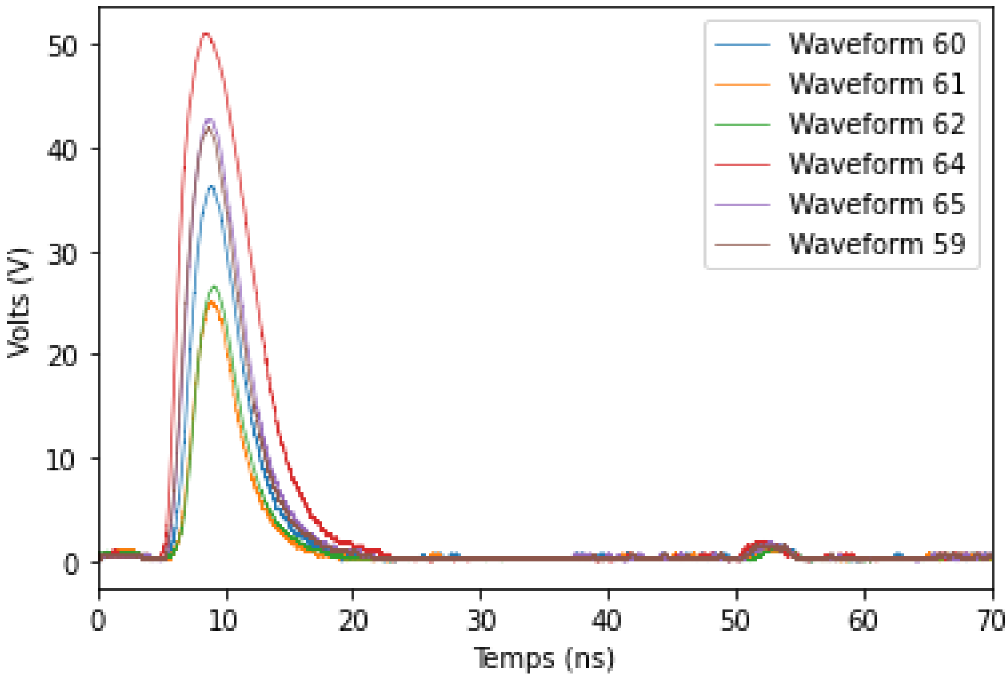


Figure 20: *Shots with different energy for the APD38*



5

Figure 21: *APD response*

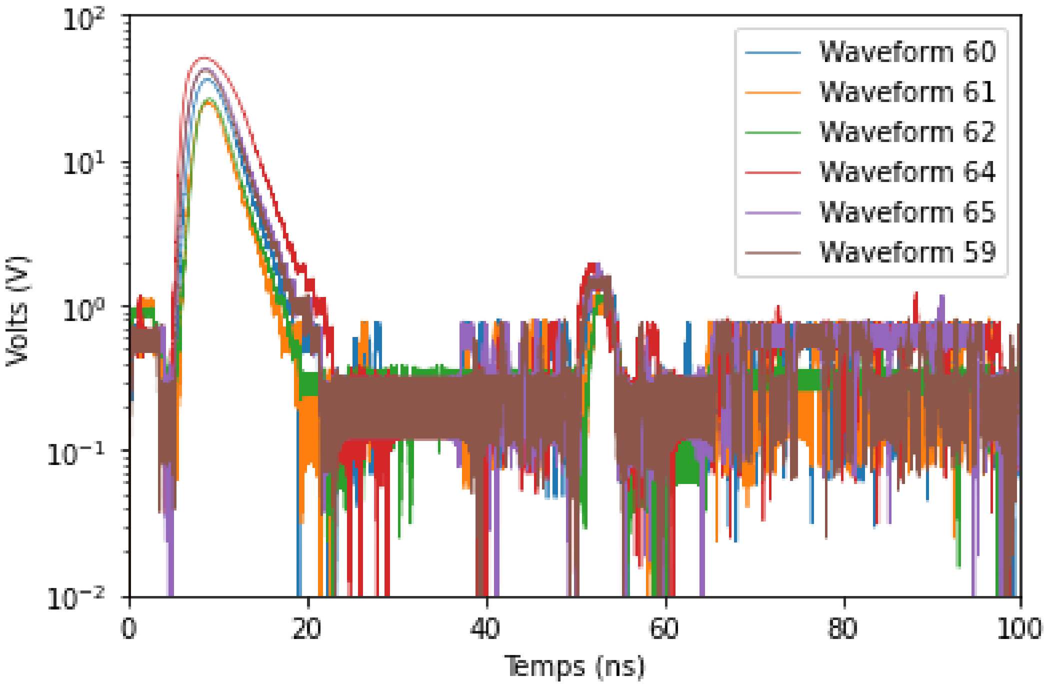


Figure 22: APD response in logarithm scale

Conclusion: It can be observed that signals with longer duration also have higher energy, whereas those with shorter duration have lower energy. It is observed that signals with higher energy, after the peak of the signal, instead of "dropping directly to the noise," exhibit a region where the signal remains elevated. This is important to know, because, when subtraction is performed, ideally, the signals from both APDs should be as similar as possible. If subtraction is done between a signal with longer duration and another one that doesn't, we would obtain a region where there is still a signal, thus delaying the time at which we can start measuring nuclear decay.

4.3 Comparison between the signals taken in 2022 and in 2023.

In this section, a comparison is presented between the signals obtained in 2023 and others taken in 2022 under similar conditions.

- Signals without the subtraction, with only one APD polarised:
  The 2023 signal has the following shape:

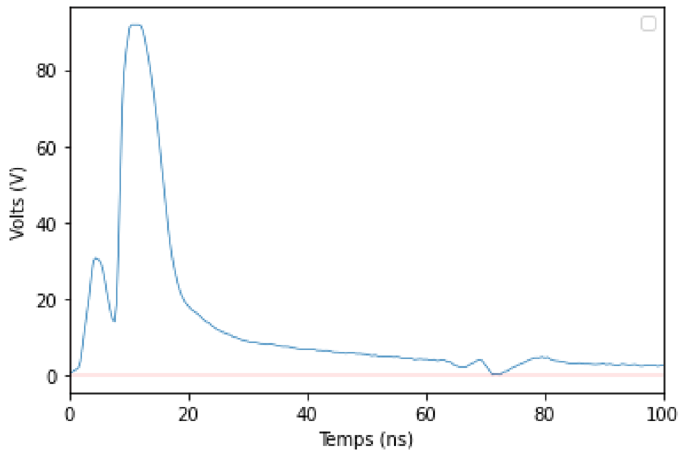


Figure 23: 2022 signal using only one APD polarised

Zooming in the Y-axis and putting the logarithm scale in the X-axis, we obtain:

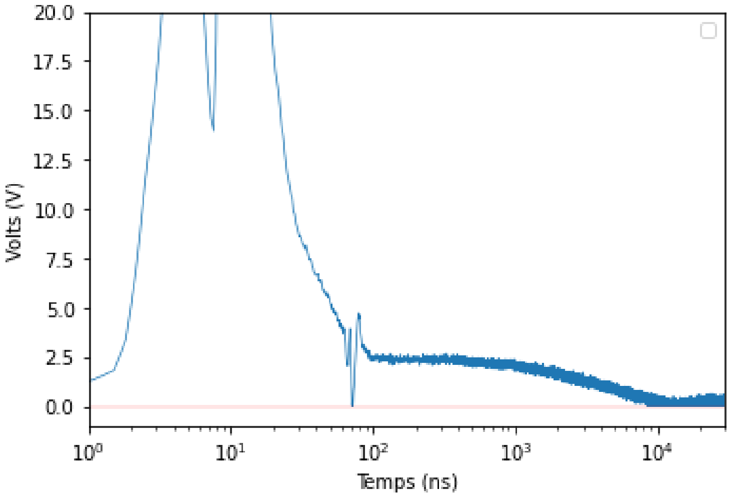


Figure 24: 2022 signal using only one APD polarised with the logarithm scale in the X-axis

Changing again the zoom and the scale:

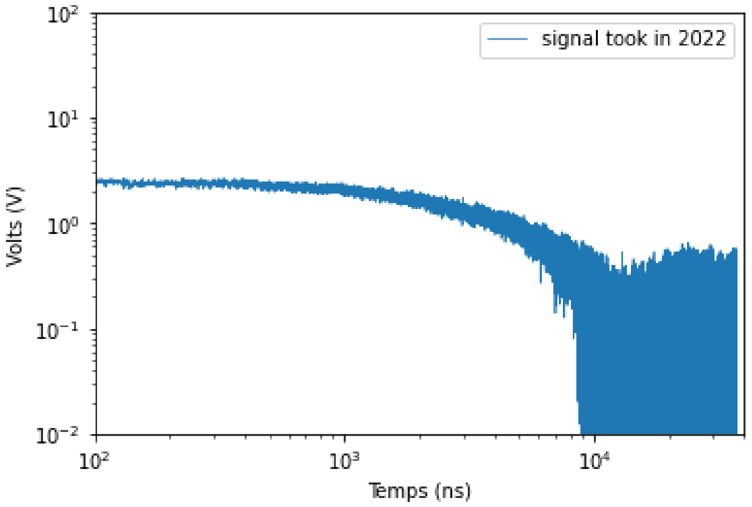


Figure 25: 2022 signal using only one APD polarised with the logarithm scale in both axis

It can be appreciated that the signal has a duration of approximately 20µs.
Plotting this signal with some of the 2023 signals:

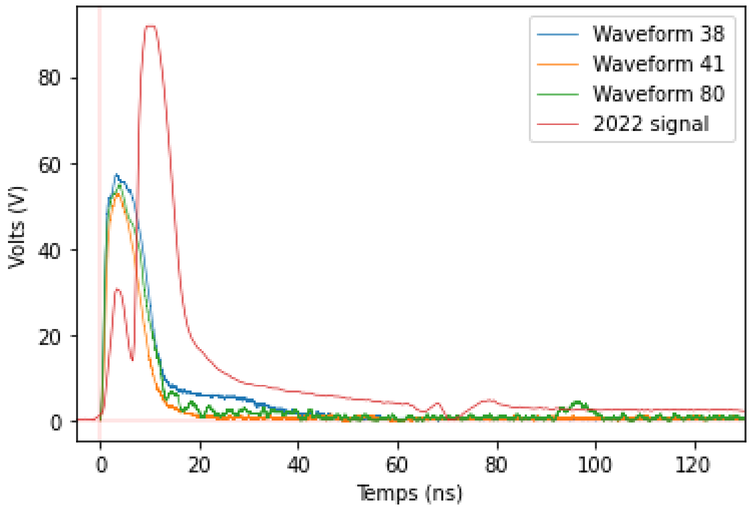


Figure 26: Comparison of some of the 2023 signals with the 2022 signal

Plotting these signals in the logarithm scale:

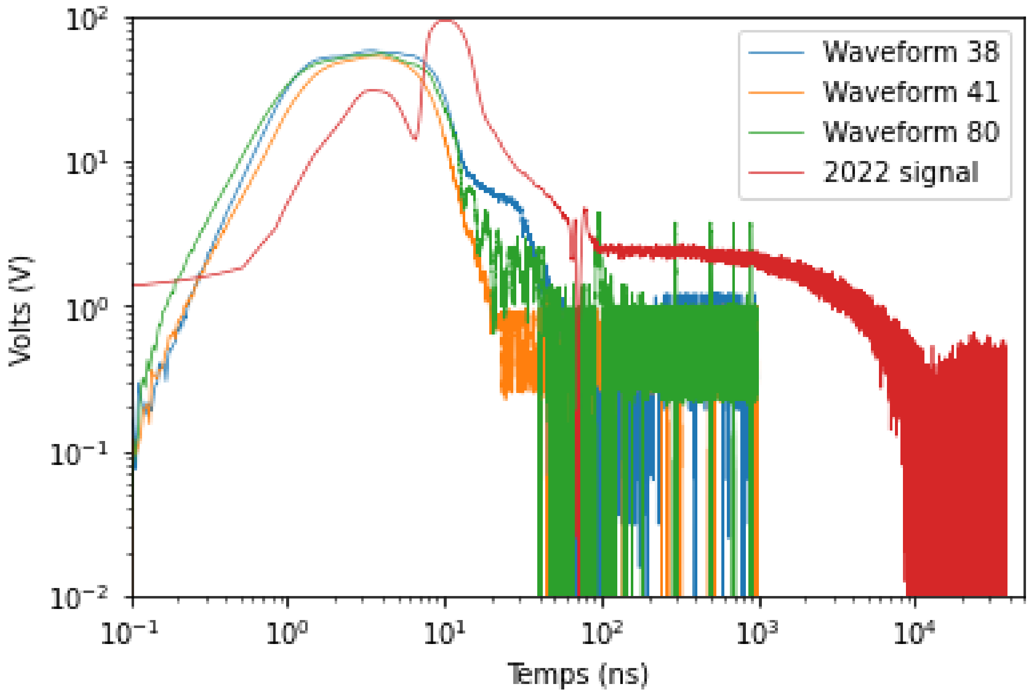


Figure 27: *Comparison of some of the 2023 signals with the 2022 signal. Logarithm scale*

<u>Conclusions</u>:
It can be observed that the 2022 signal has a higher amplitude (approximately 90V) than the 2023 signals.
Furthermore, the duration of the signals is significantly different. The 2023 signals have a duration of approximately 20 to 60 ns, whereas the 2022 signal has a duration of approximately 20µs.

- Signals with the subtraction, with both APDs polarised:

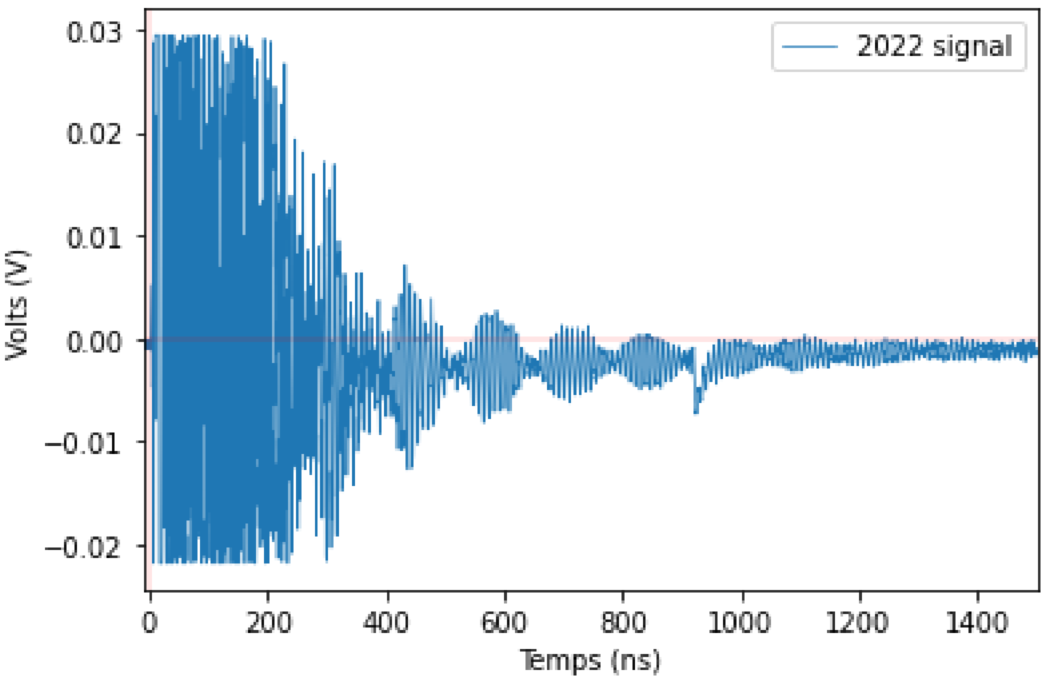


Figure 28: *2022 subtracted signal*

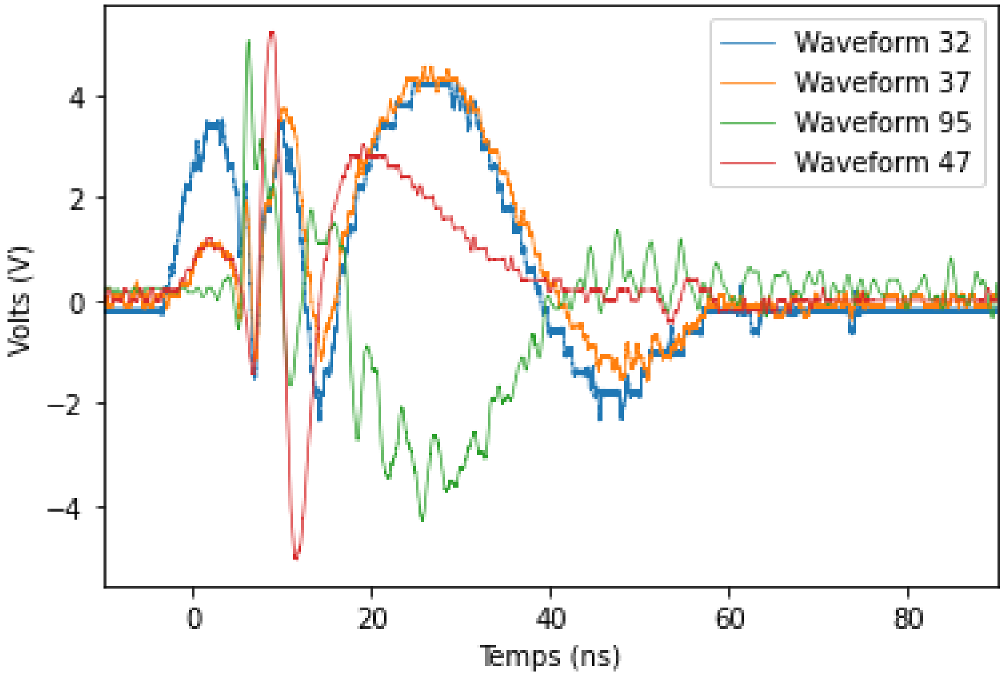


Figure 29: Some 2023 subtracted signals.

Conclusions:
It is observed that the 2023 signals have a much shorter duration than the signal captured in 2022. The 2022 signal has a duration of about 1000ns whereas the 2022 signals of about 70 ns. The fact that the signals have a shorter duration represents a significant advantage, as it would be possible to start measuring the radiation emitted by 181Ta much earlier.
However, it is also observed that the subtracted 2022 signal has an amplitude of approximately 50 mV, while those of 2023 have an amplitude ranging between 5 and 9 volts.
In the following section, the subtraction will be studied in greater depth.

5. Subtraction signals.

In this section it will be given a study of the experimental subtracted signals. With the aim of determining if the experimental subtraction is being performed correctly, it will be shown the results obtained by subtracted two one APD polarised signals numerically in Python.

5.1 Numerical subtraction.

So as to see if the experimental subtraction has been done correctly, the python program that computes the subtraction of two signals has been coded. This program, before performing the subtraction of two given signals, raises the signal that has a lower height to the one that has a higher height. Then, it moves both signals so as to have the starting point of both at the same place. This is done in order to make the subtracted signal more accurate. Finally, it computes the subtracted signal. In the following images is presented an example of use with the signals 40 and 41.
The following 4 images depict the process performed by the program. The top-left image represents the two signals without applying any transformation. The top-right image shows the two images again, but with the lower signal (41) previously multiplied by a factor to raise them to the same height. The top-left image displays the two signals shifted so that they start at the same point. Finally, the last image shows the subtracted signal of both.

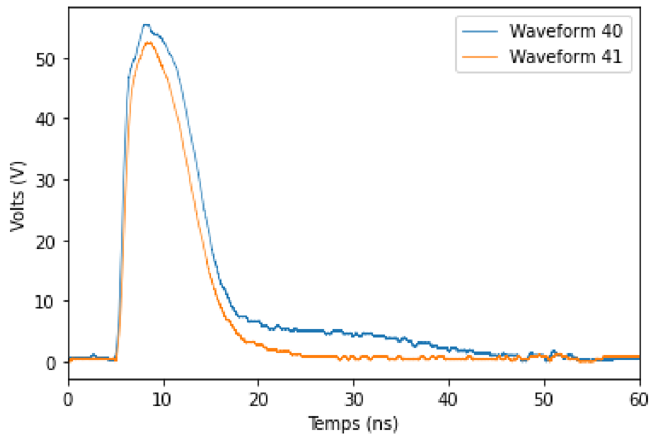


Figure 30: signals 40 and 41

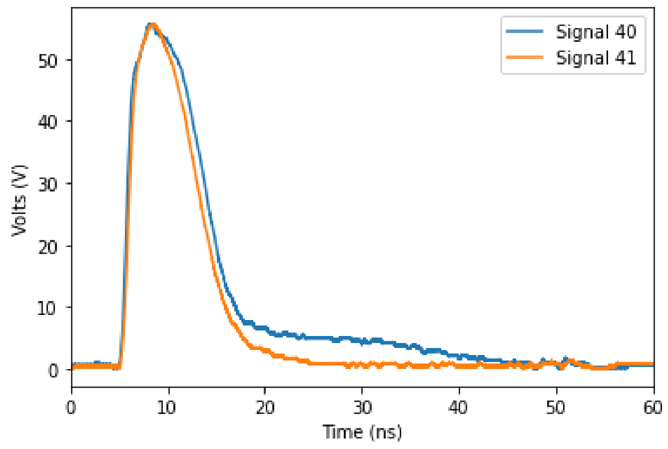


Figure 31: Signals 40 and 41 with the same high

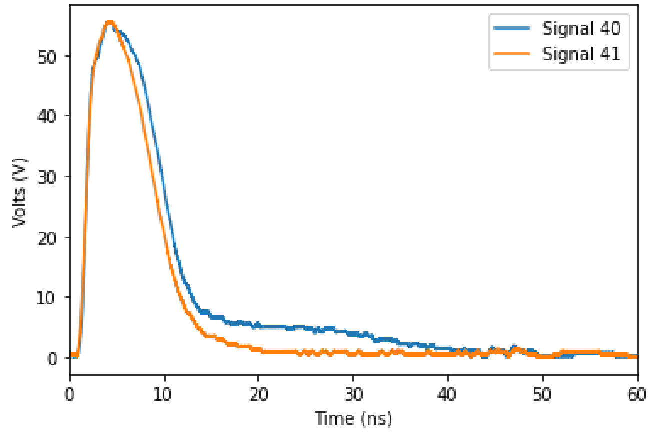


Figure 32: Signals 40 and 41 with the same height and shifted

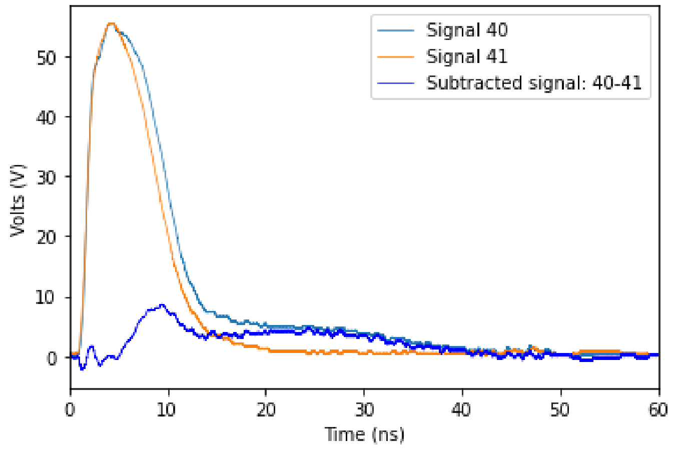


Figure 33: Numerical subtracted signal

And the plotting only the subtracted signal:

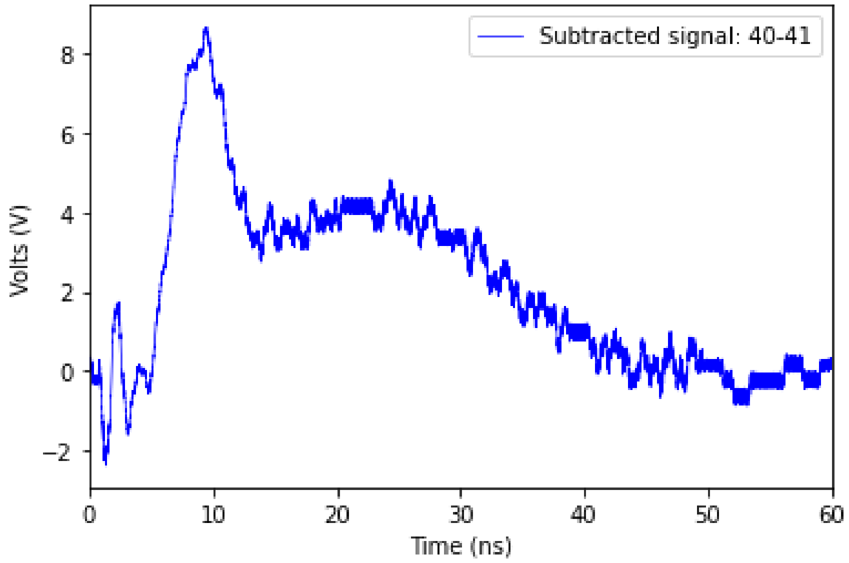


Figure 34: Numerical subtracted signal

The next section includes several graphs obtained by numerically subtracting various pairs of signals. This numerical result will be compared with several experimental subtracted signals.

5.2 Experimental subtraction and comparison with the numerical subtraction.

In this section it will be shown some of the subtracted experimental signals. That is, some signals that have been obtained with the transformer by subtracting the signals captured using two APDs polarised. A comparison is shown between these signals and some signals obtained by performing numerical subtraction. In order for the comparison to be more accurate, the three signals that have been considered, that is, the transformer output signal and the two signals with a single polarized APD that we have numerically subtract, have been taken under similar experimental conditions.

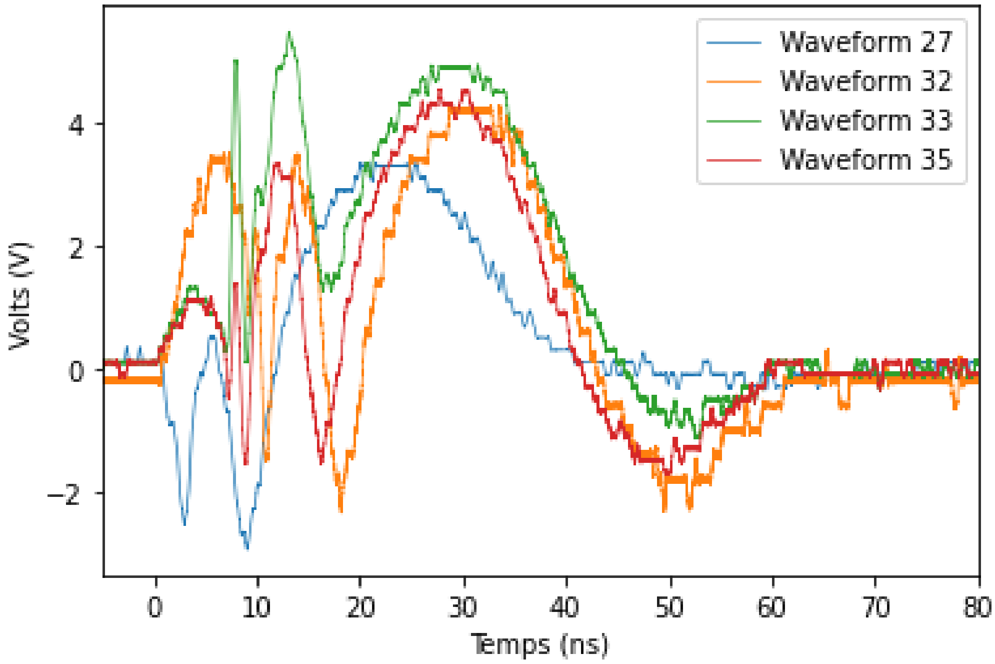


Figure 35: *Experimental subtracted signals using APD34 and APD36*

Numerical subtracted signals:

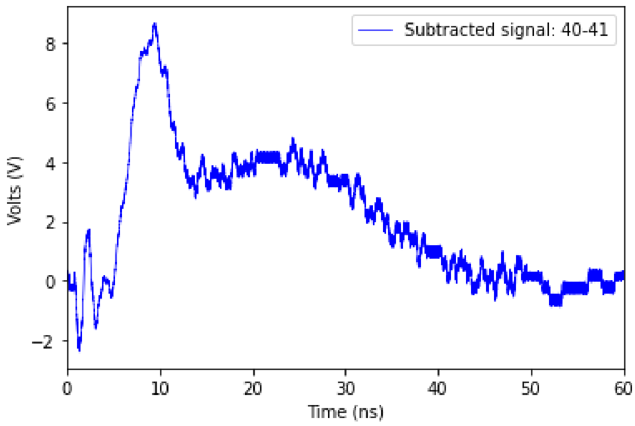


Figure 36: *Numerical subtracted signal: 40-41*

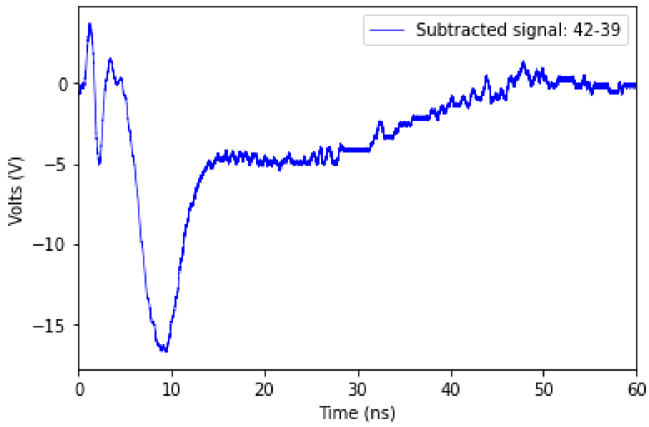


Figure 37: *Numerical subtracted signal: 42-39*

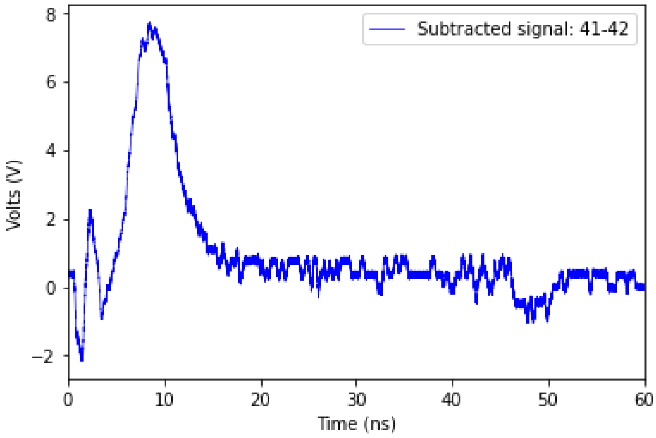


Figure 38: *Numerical subtracted signal: 41-42*

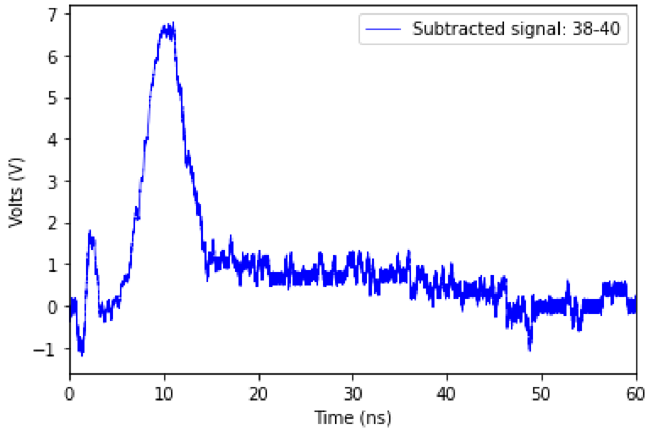


Figure 39: *Numerical subtracted signal: 38-40*

Proceeding in the same way:

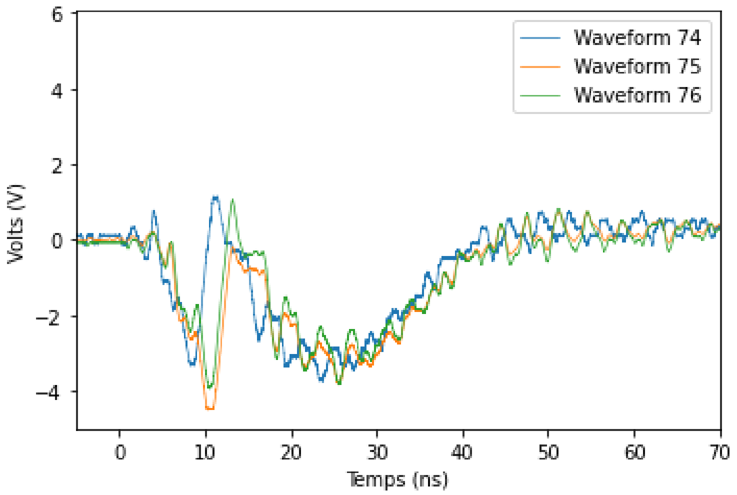


Figure 40: *Experimental subtracted signals using APD34 and APD36*

Numerical subtracted signals:

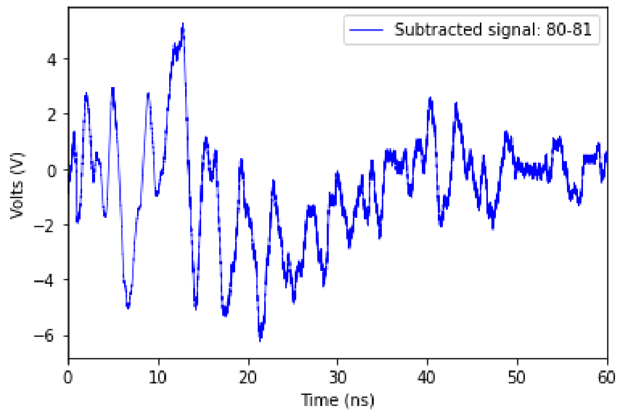


Figure 10: Numerical subtracted signal: 80-81

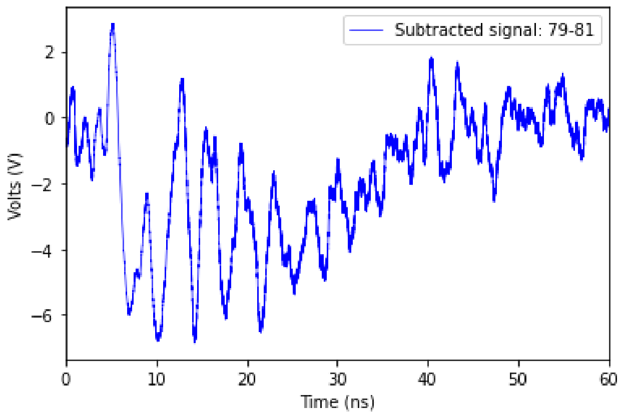


Figure 11: Numerical subtracted signal: 79-81

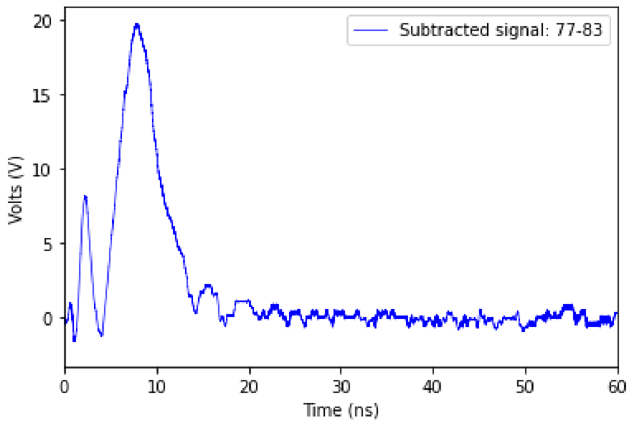


Figure 12: Numerical subtracted signal: 77-83

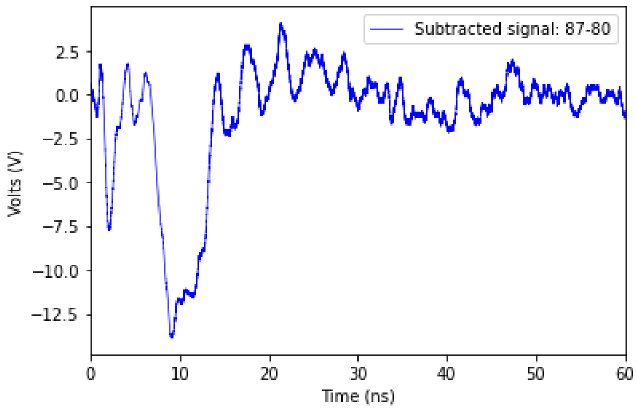


Figure 13: Numerical subtracted signal: 87-80

Proceeding again in the same way:

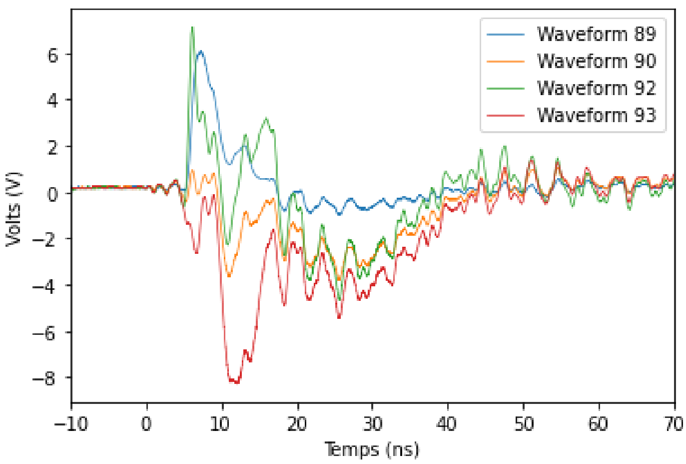


Figure 14: Experimental subtracted signals using APD34 and APD36

Numerical subtracted signals:

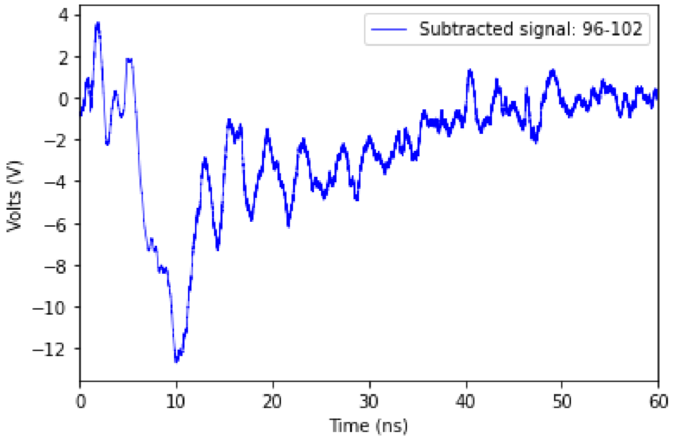


Figure 15: *Numerical subtracted signal: 96-102*

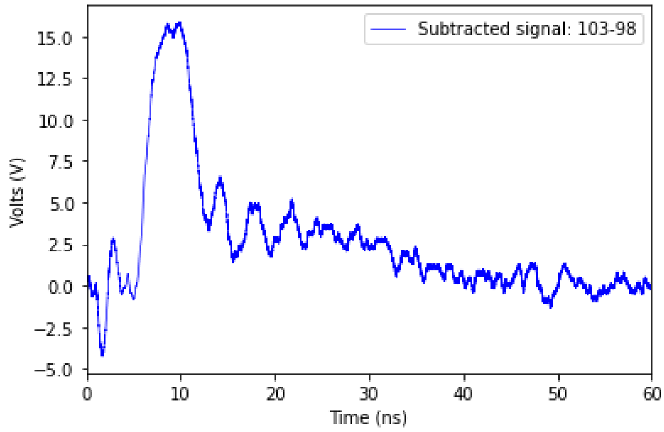


Figure 16: *Numerical subtracted signal: 103-98*

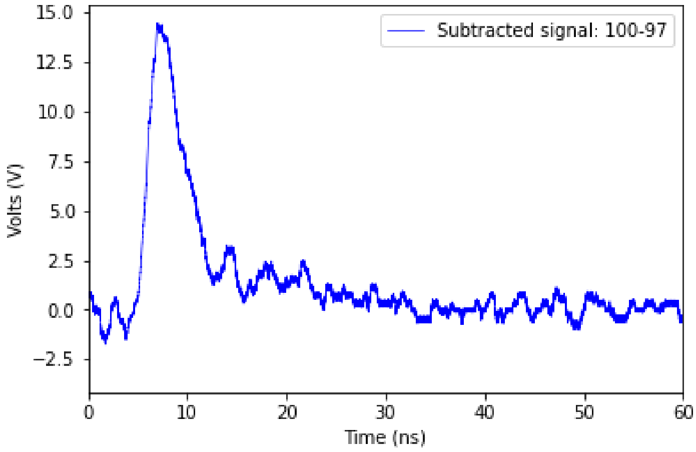


Figure 17: *Numerical subtracted signal: 100-97*

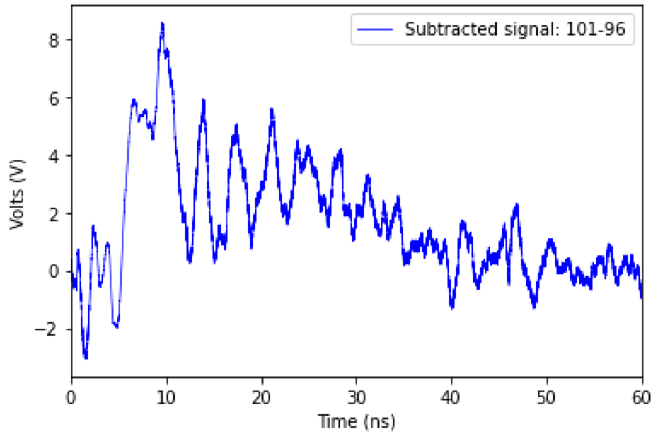


Figure 18: *Numerical subtracted signal: 101-96*

And proceeding in the same way one last time.

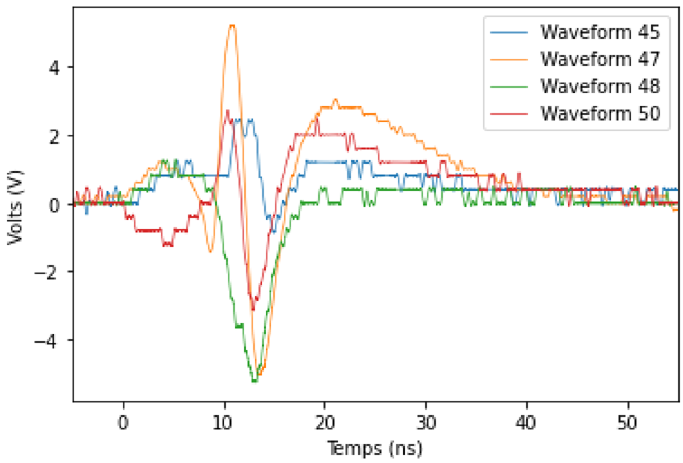


Figure 50: *Experimental subtracted signals using APD37 and APD38*

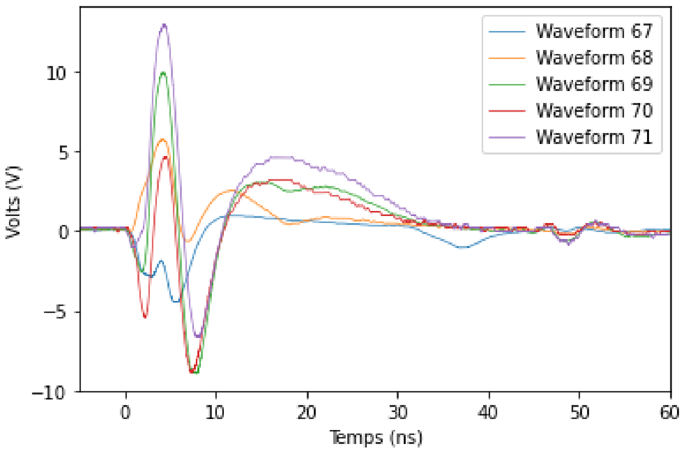


Figure 19: *Experimental subtracted signals using APD37 and APD38*

Numerical subtracted signals:

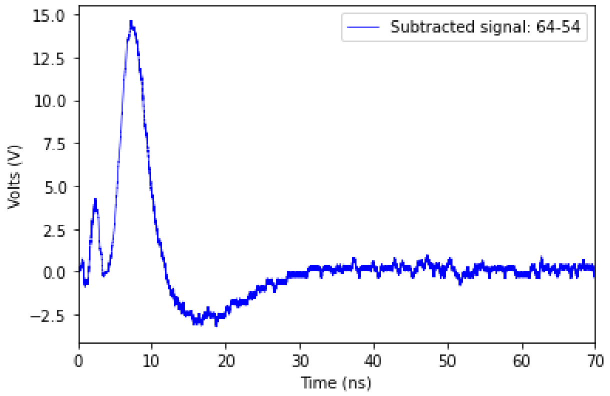


Figure 20: Numerical subtracted signal: 64-54

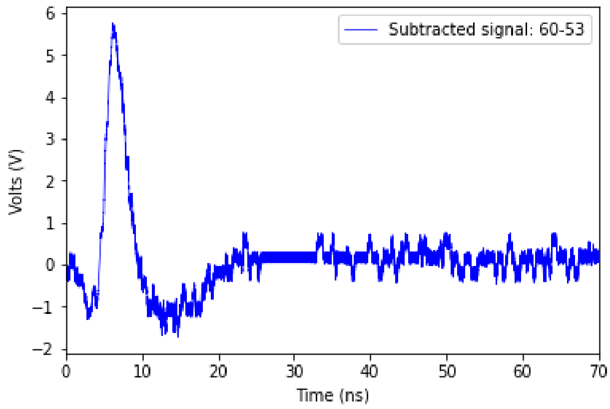


Figure 21: Numerical subtracted signal: 60-53

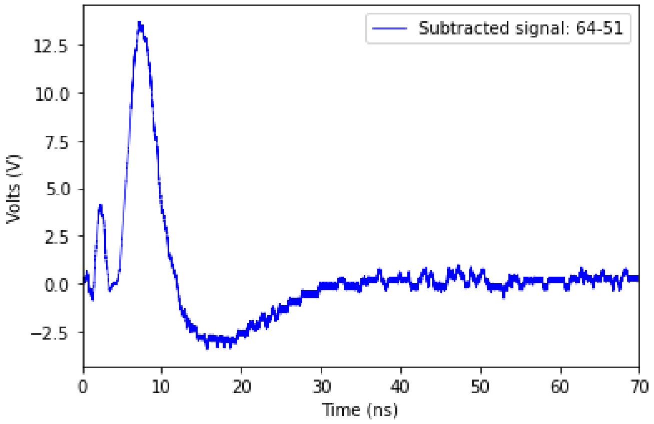


Figure 22: Numerical subtracted signal: 64-51

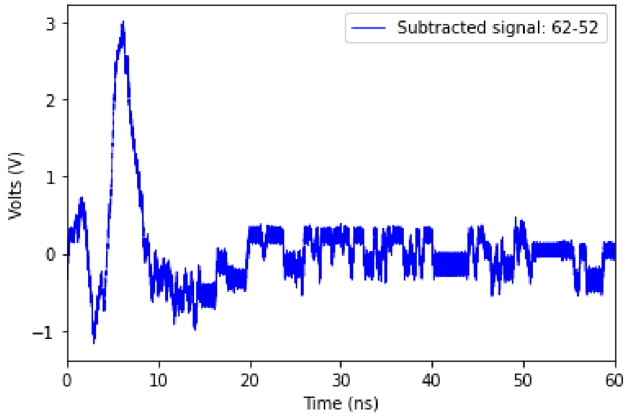


Figure 23: Numerical subtracted signal: 62-52

Conclusion:

Observing the graphs, it can be appreciated that the durations of the numerical signals are quite similar that of the experimental signals. We can also appreciate that the maximum amplitudes of the experimental signals generally have a lower value. However, they are of the same order of magnitude. Therefore, since the experimental and numerical signals are quite similar, we can conclude that the subtraction performed using the transformer is being carried out correctly.