PMT Simulation

noise, SPE signal characterization and code updates

Presented by: Luan Gomes

Universidade Federal de Juiz de Fora (UFJF)

with ***Davide Pinci*** *(INFN-Roma I) and* ***Rafael A. Nóbrega*** *(UFJF)*

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Summary

In this presentation:

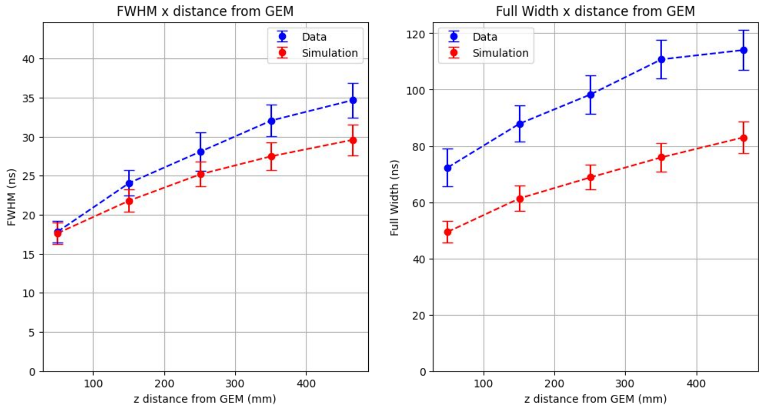
1. Introduction
2. Noise simulation
3. SPE Signal characterization
4. Code updates
5. Conclusions

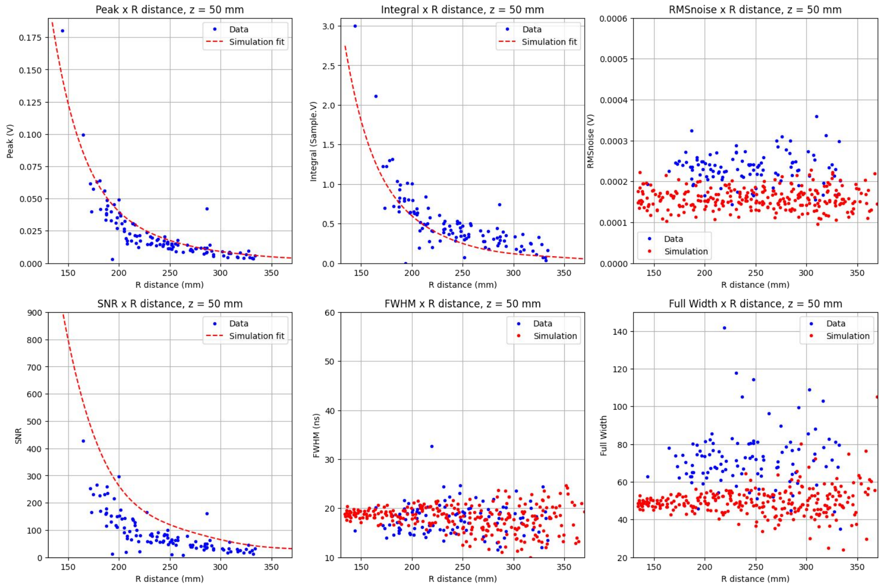
Introduction

From my last presentation…

Sim/data comparison - 55Fe events

- Simulation/data main differences:
  - RMS noise
  - Waveform shape

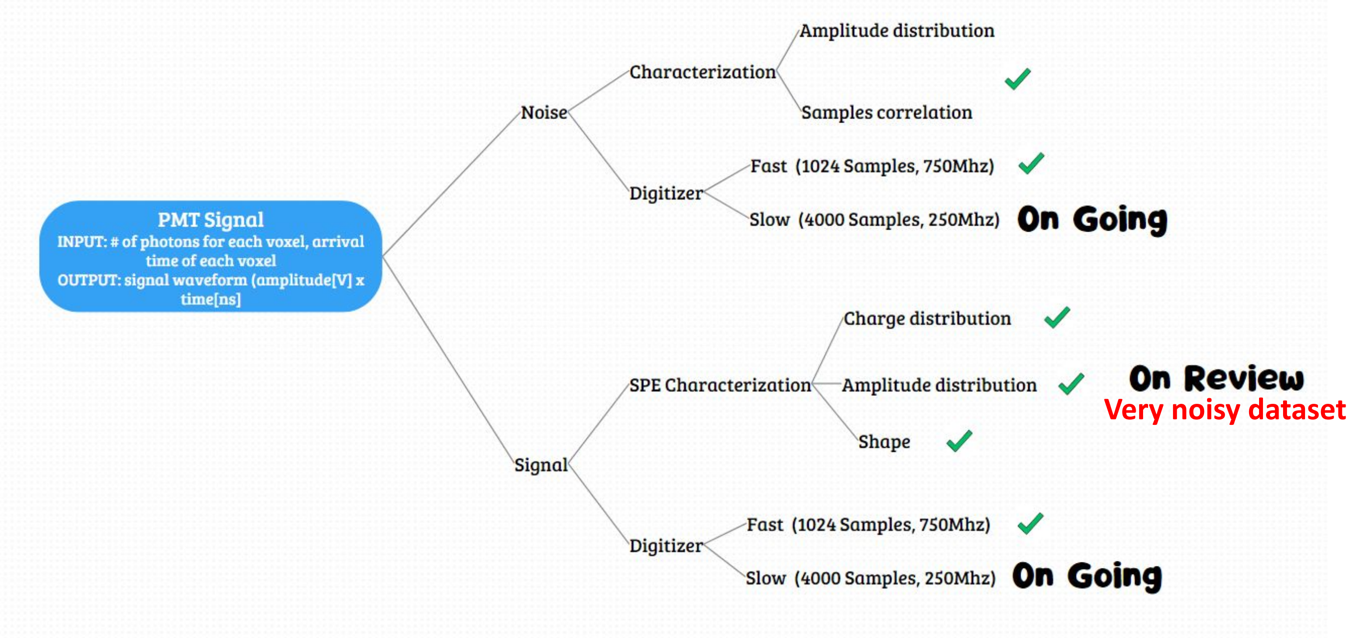




Introduction

From my last presentation…

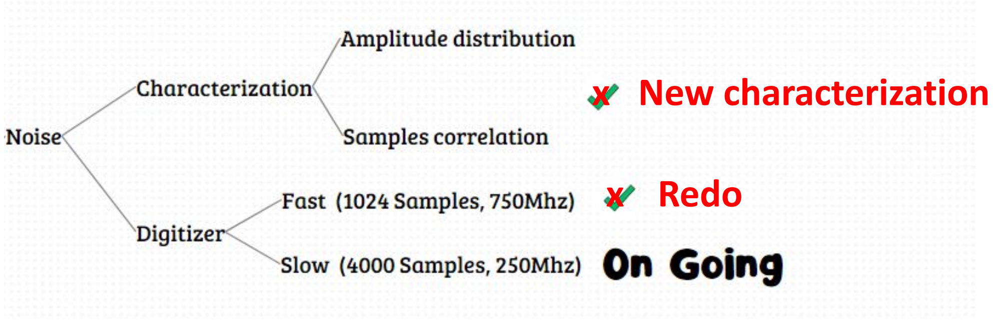
PMT Simulation tasks



Introduction

PMT signal simulation

- Currently we simulate only the fast digitizer
- To simulate the fast and slow digitizers, we need to perform noise characterization
    - Redo the characterization for fast digitizer



Noise simulation

Current method

- Generate the noise from covariance matrix of a noise dataset (random.multivariate_normal)

Problems:

- The current cov matrix is not correct
  - I have done the characterization of the noise for channels that the PMTs are not connected.

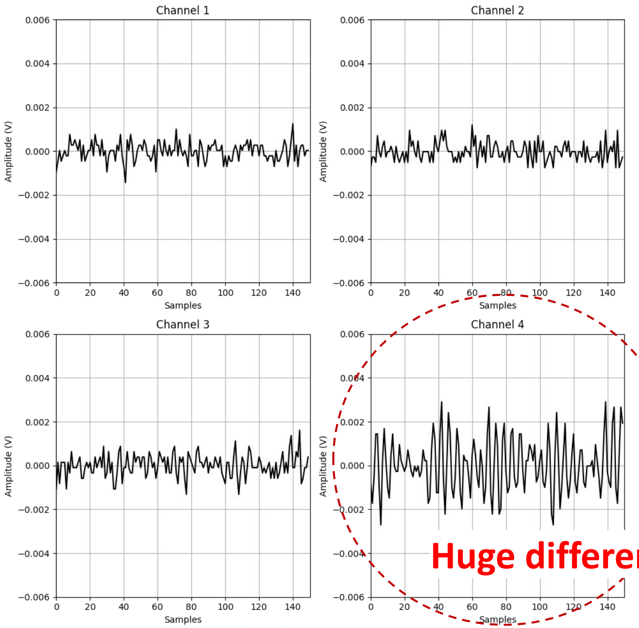
New method

- Generate the noise from Power Spectral Density of a noise dataset
  - Get the Average Power Spectral Density of the dataset
  - Generate a random phase from a uniform distribution
  - Perform an IFFT to obtain the time-domain noise series
- Faster than current method

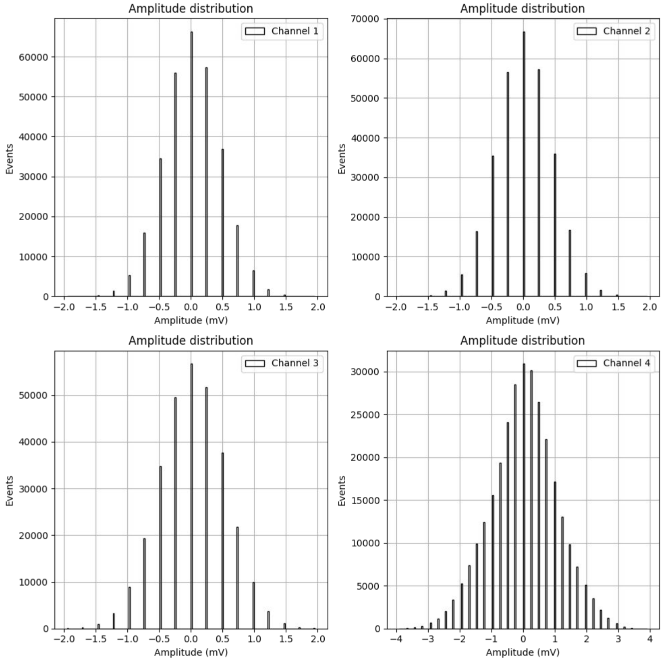
Noise simulation

The noise dataset - run 60880 - 2000 noises/channel

Fast digitizer - First 150 samples



REAL DATA



Noise signals appear identical for channels 1 and 2

Huge difference

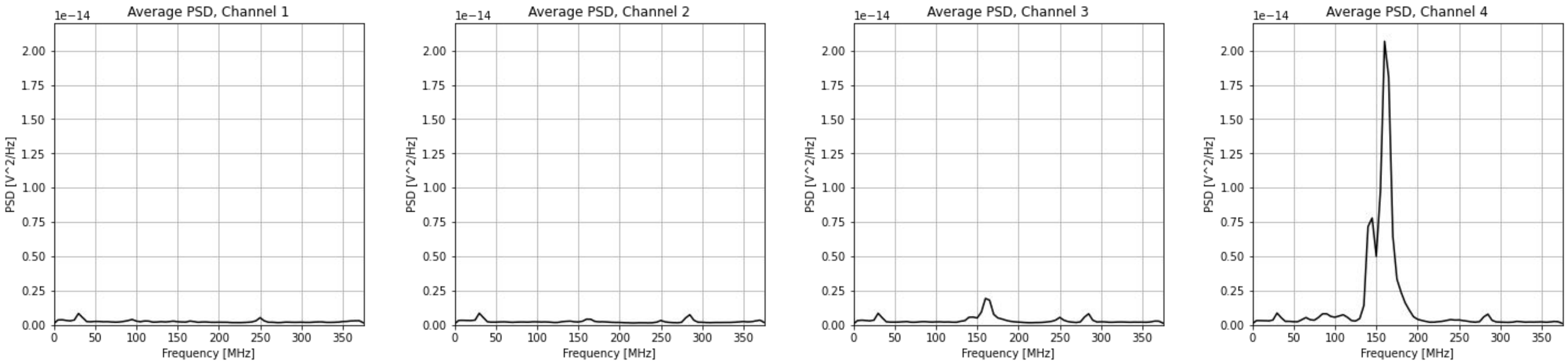
- Should we perform the characterization for each channel?
- Or a single characterization for all channels?

Noise simulation

The noise dataset - run 60880 - 2000 noises/channel

Fast digitizer - First 150 samples

- Let’s take a look at the Average Power Spectral Density

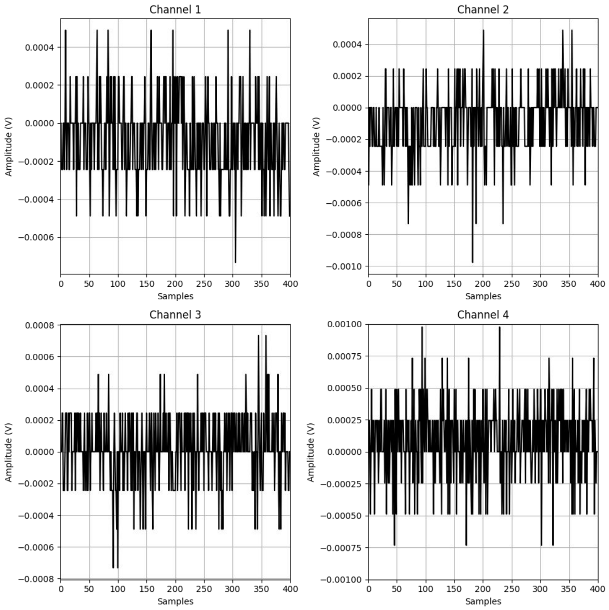


- A characterization for each channel may be the best approach

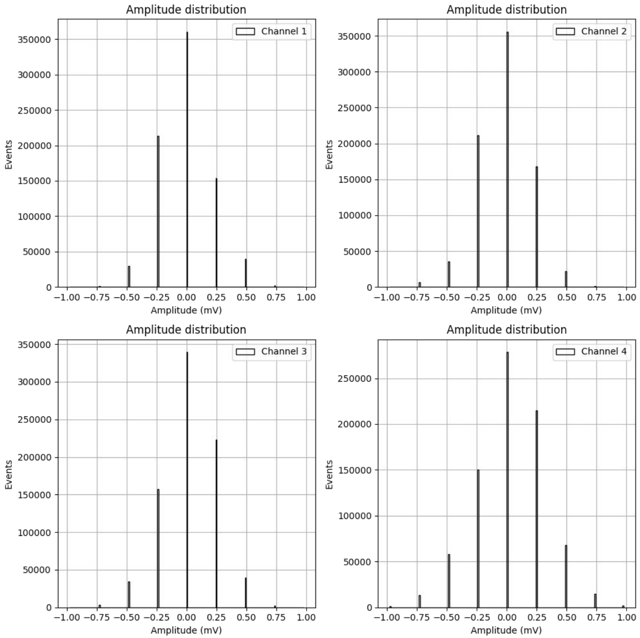
Noise simulation

The noise dataset - run 60880 - 2000 noises/channel

Slow digitizer - First 400 samples



REAL DATA

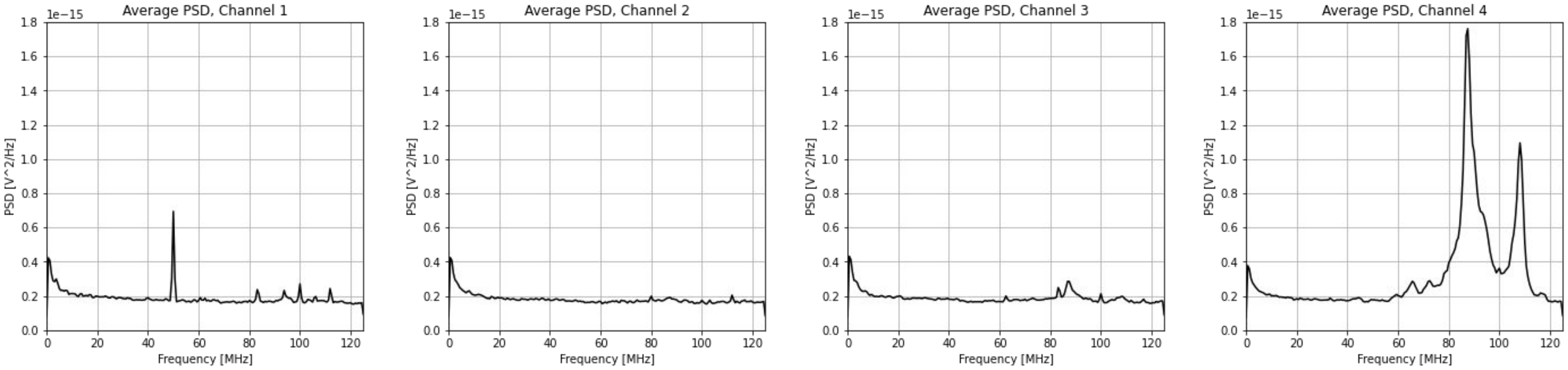


Noise simulation

The noise dataset - run 60880 - 2000 noises/channel

Slow digitizer - First 400 samples

- Let’s take a look at the Average Power Spectral Density



- A characterization for each channel may be the best approach

Noise simulation

Quantization

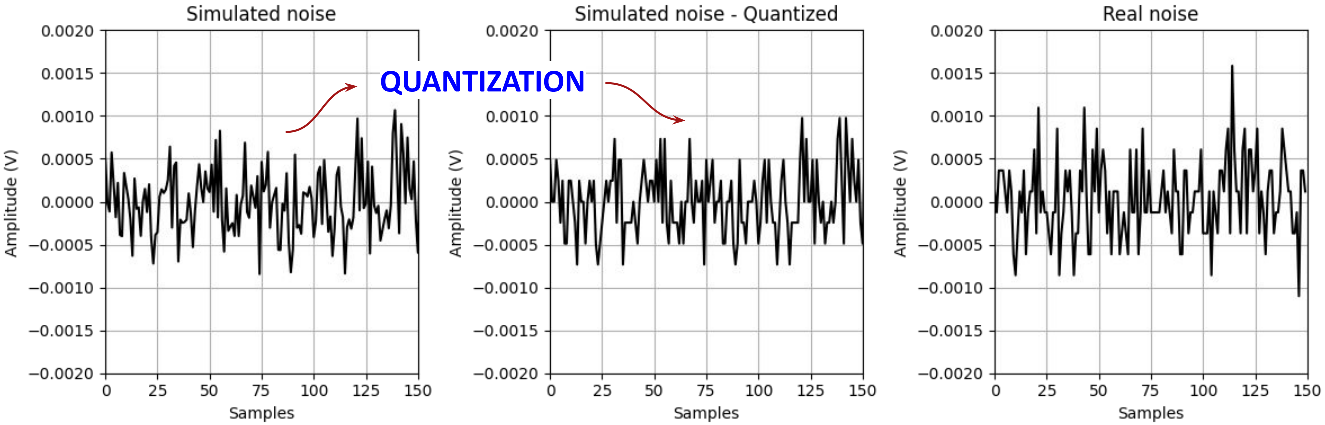
- The current simulation do not apply quantization to the simulated waveforms

ADC: 12 bit

Resolution: 1V / 4096

Fast digitizer - 750MS/s | 1024 Samples

Channel 1 Example



Noise simulation

Quantization

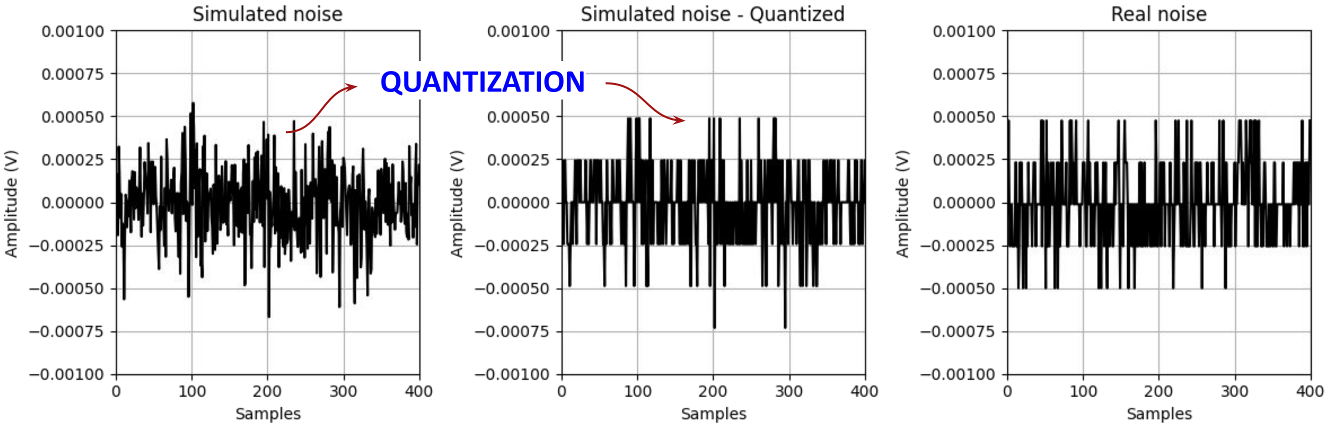
- The current simulation do not apply quantization to the simulated waveforms

ADC: 12 bit

Resolution: 1V / 4096

Slow digitizer - 250MS/s | 4000 Samples

Channel 1 Example



The effect of quantization is more noticeable in the slow digitizer

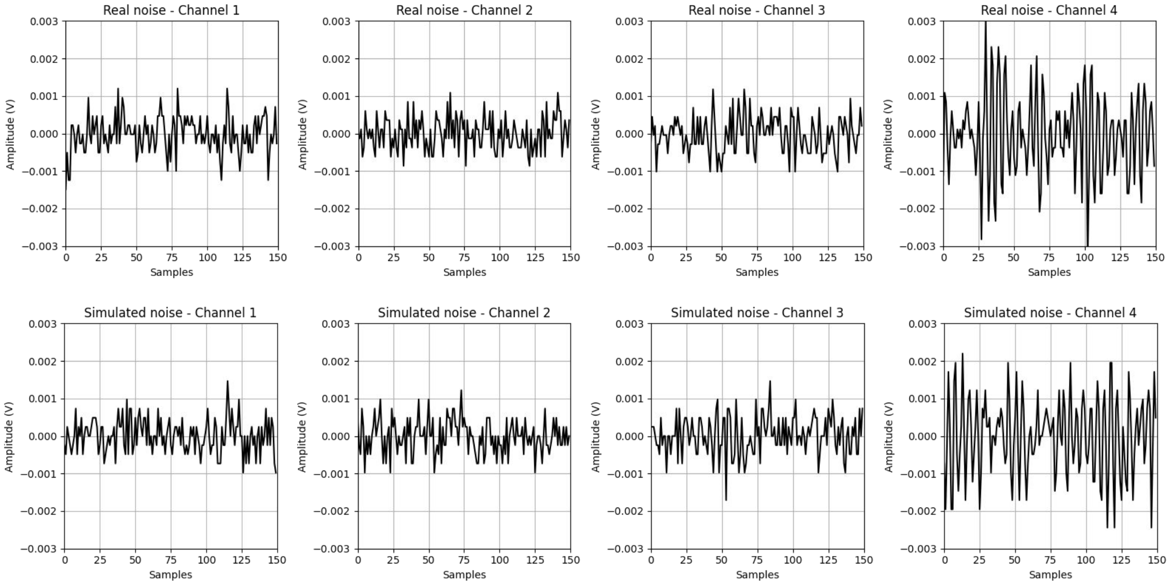
Noise simulation

Simulation/Real noises comparison - Waveforms

Fast digitizer - First 150 samples

REAL

SIMULATION



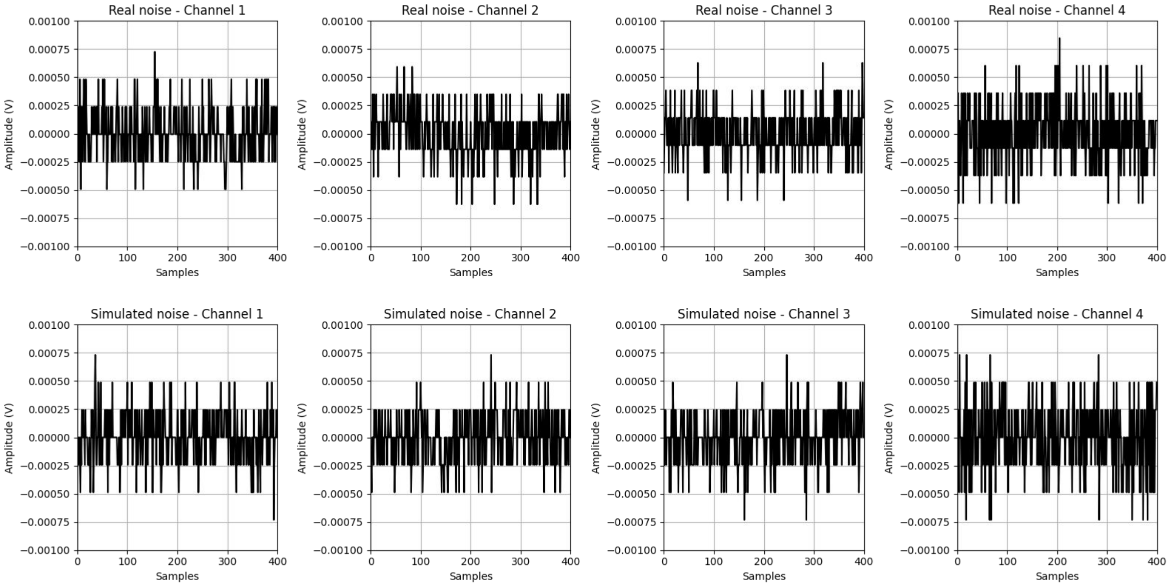
Noise simulation

Simulation/Real noises comparison - Waveforms

Slow digitizer - First 400 samples

REAL

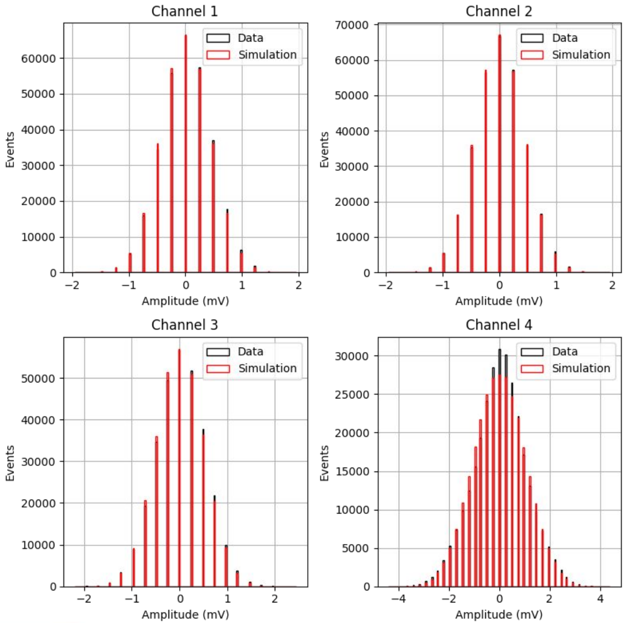
SIMULATION



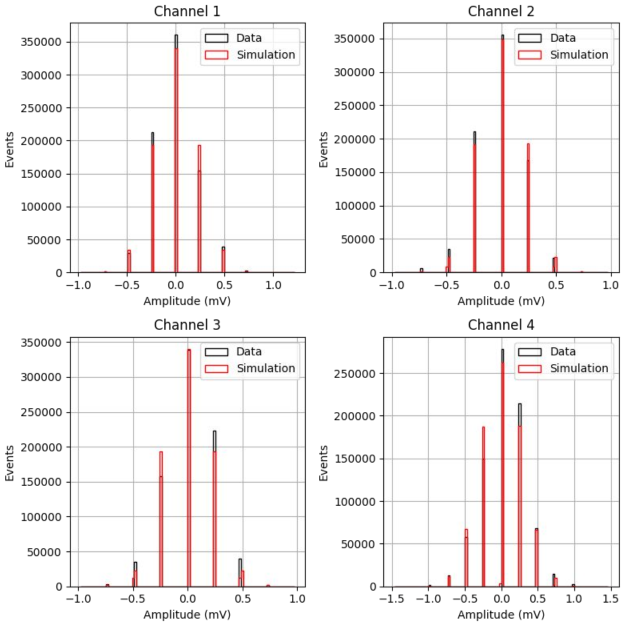
Noise simulation

Simulation/Real noises comparison - Amplitude distribution

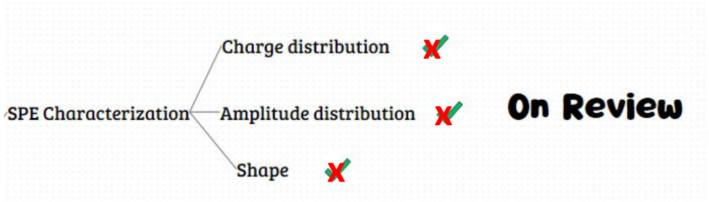
Fast digitizer



Slow digitizer

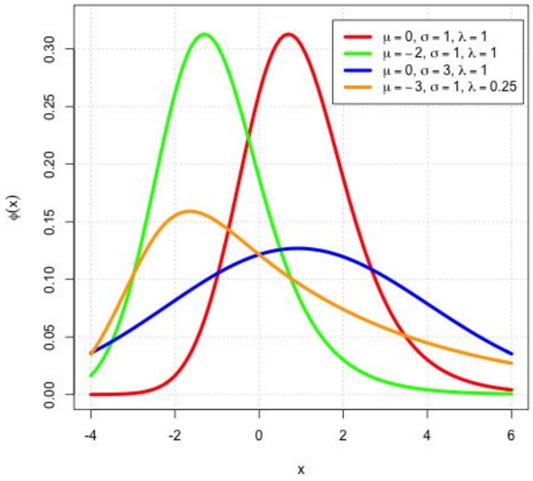


SPE signal characterization



Signal shape model

- Currently we represent the SPE signal shape as a Gaussian
- We were able to estimate a new SPE signal shape using an Exponentially modified Gaussian



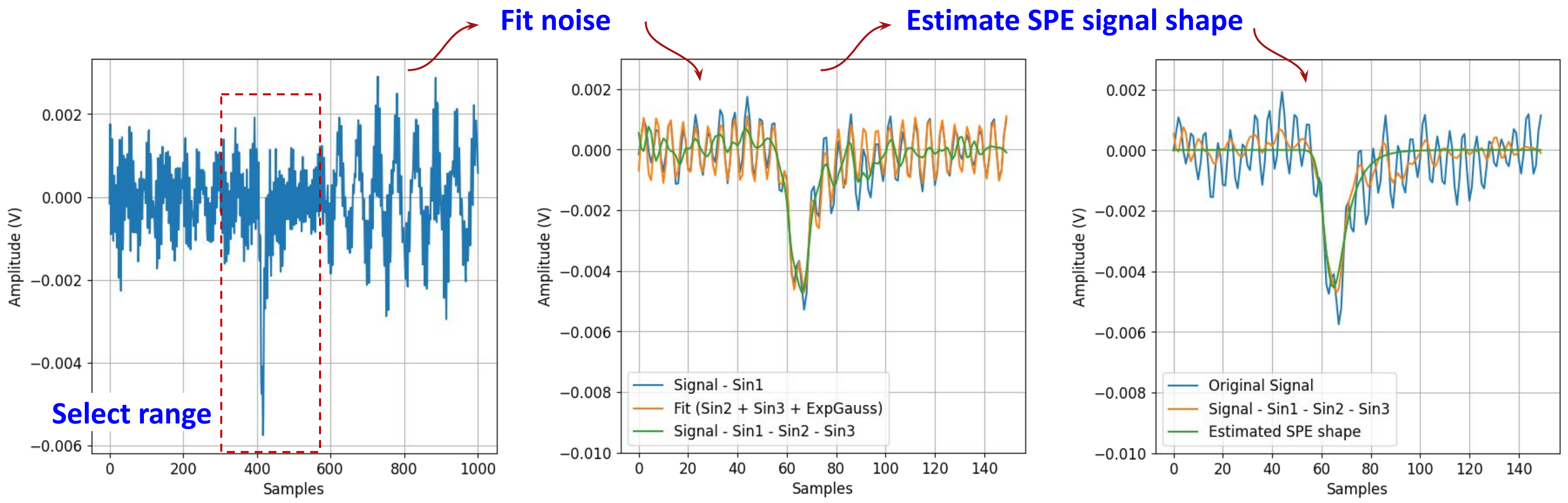
$$f(x;\mu,\sigma,\lambda) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right)$$

- μ = mean (arrival times)
- σ = standard deviation (width)
- λ = exponential decay rate

SPE signal characterization

Remembering the characterization

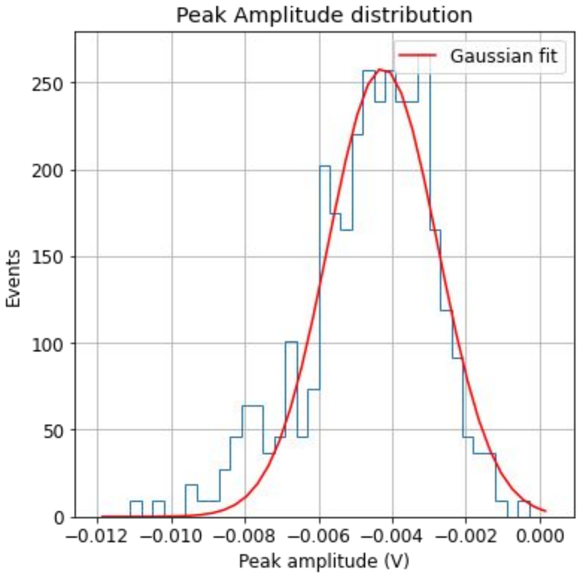
Example

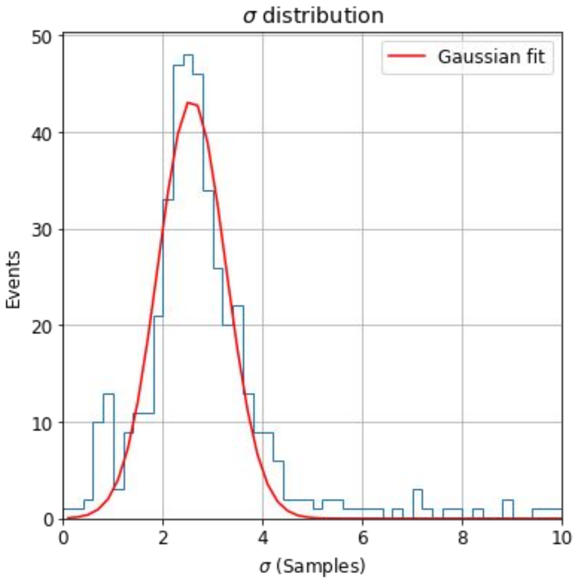


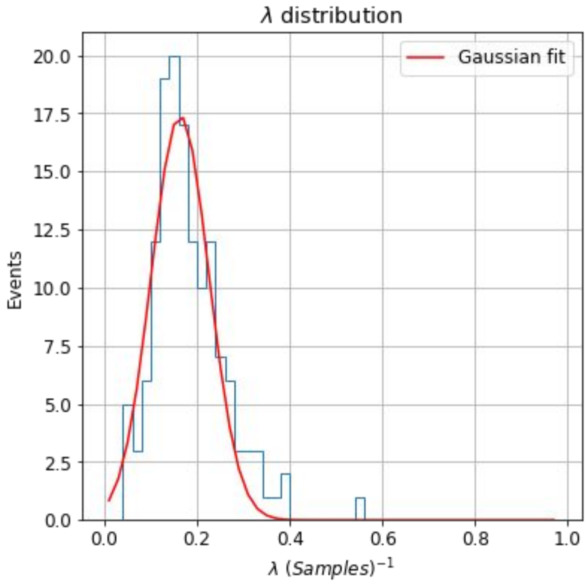
Dataset: …/PMT-Test-270922/BA1642_single_photoelectron

SPE signal characterization

New results

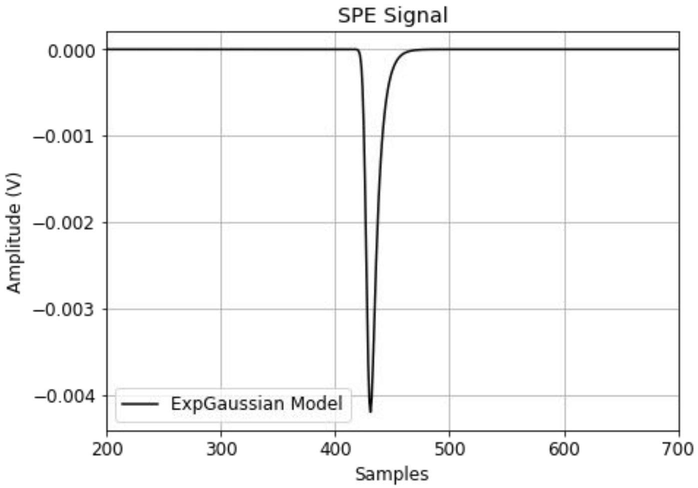






SPE signal characterization

New results

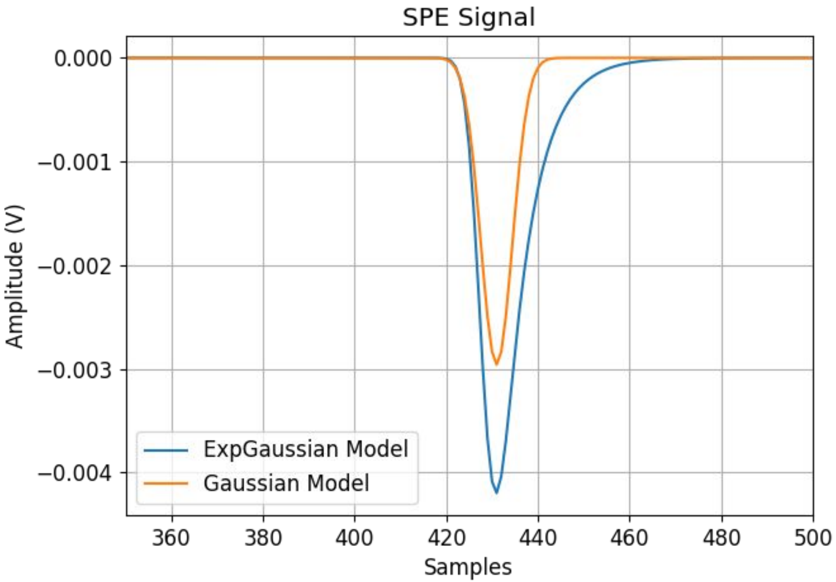


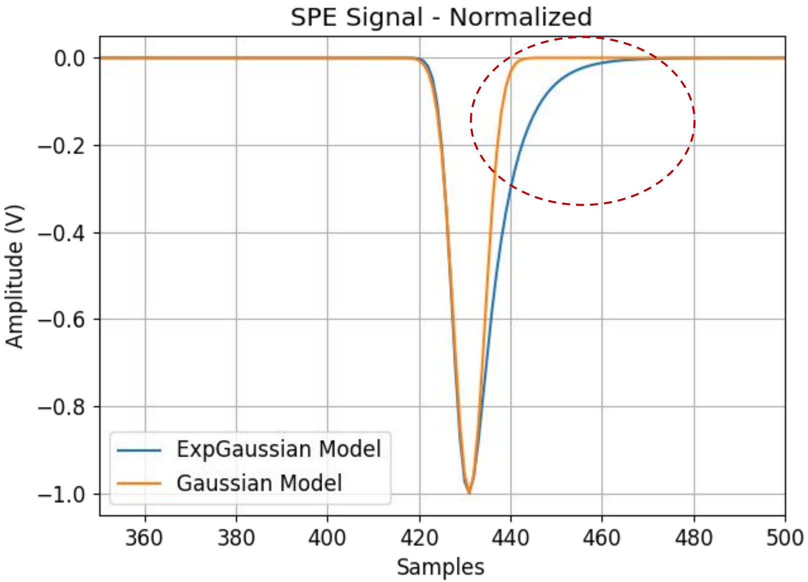
SPE acquisition setup: 5GS/s -> 1 Sample = 0.2 ns

- Amplitude: mean = -0.0042 V, std = 0.00148 V
- σ = 2.63 Samples = 0.53 ns
- $\lambda = 0.163\ (\text{Samples})^{-1} = 0.81\ (\text{ns})^{-1}$
- Rise time
  - 6 Samples = 1.2 ns
  - PMT R7378A Datasheet: 1.5 ns (Typical)
- Fall time
  - 14 Samples = 2.8 ns

SPE signal characterization

Old vs new SPE signal



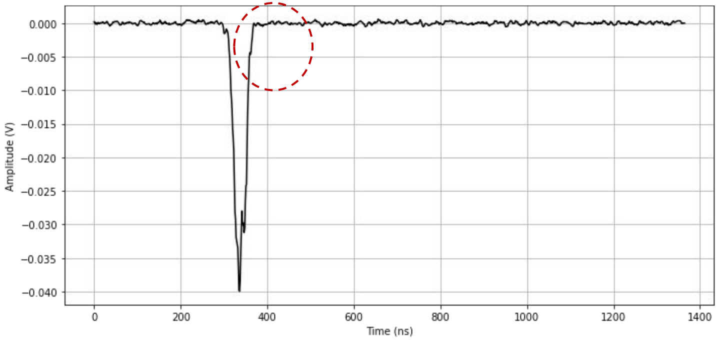


SPE signal characterization

Shape problem

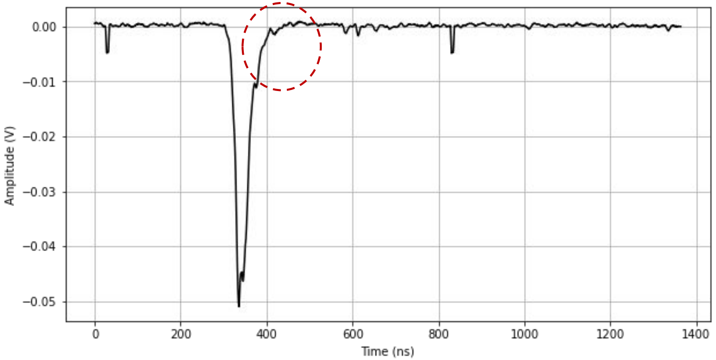
- The modification of the SPE signal shape is not enough to fix the “tail” of the waveforms:

SIMULATION



CYGNO_60_40_ER_6_keV

REAL



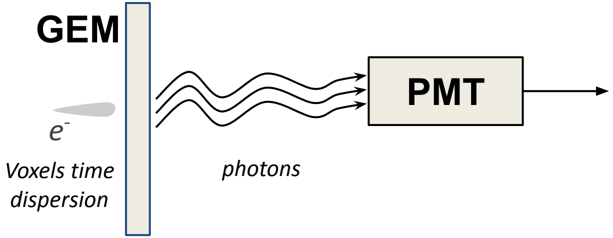
Example for 55Fe spot - Step 5 = 46.6 cm **(moving average filter applied to the waveforms in this example)**

SPE signal characterization

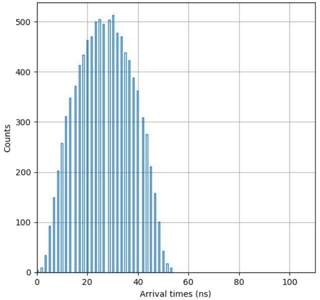
Shape problem

From detector simulation:

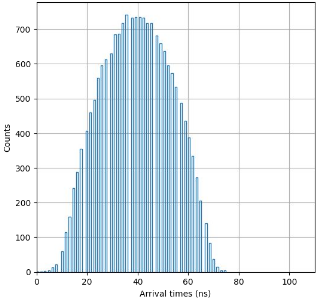
- Voxels arrival times:
  - Follows a Gaussian Distribution



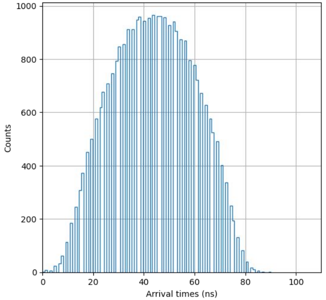
Step 1 = 5.0 cm



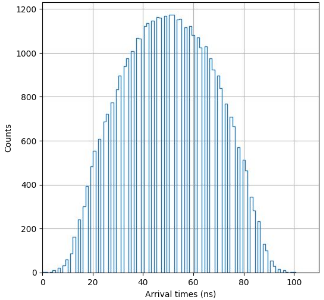
Step 2 = 15.1 cm



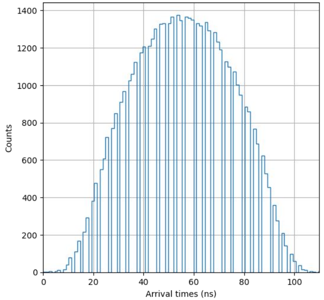
Step 3 = 25.1 cm



Step 4 = 35.1 cm



Step 5 = 46.6 cm



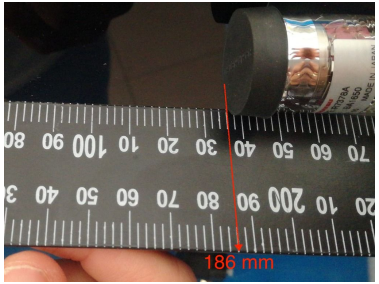
CYGNO_60_40_ER_6_keV

Code updates

Correction

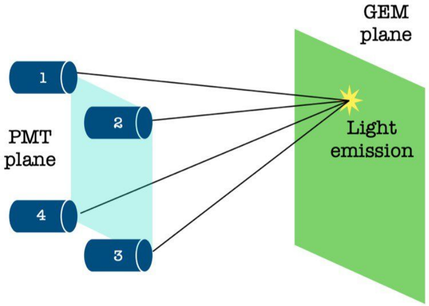
PMTs positions

- Coordenates



Before	Now
Z distance from GEM plane = 134	Z distance from GEM plane = 186
PMT 1: X = 312, Y = 312	PMT 1: X = 42, Y = 312
PMT 2: X = 312, Y = 42	PMT 2: X = 312, Y = 312
PMT 3: X = 42, Y = 42	PMT 3: X = 312, Y = 42
PMT 4: X = 42, Y = 312	PMT 4: X = 42, Y = 42

Units in mm



Code updates

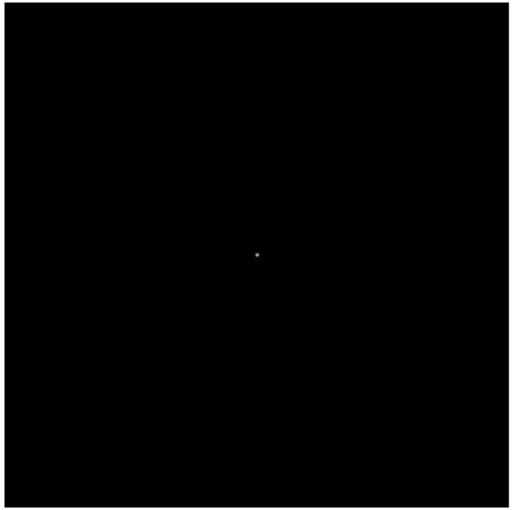
New parameters in PMT simulation config file

```
{"pmt_positions": {"pmt_1": {"x": 42, "y": 312},
                   "pmt_2": {"x": 312, "y": 312},
                   "pmt_3": {"x": 312, "y": 42},
                   "pmt_4": {"x": 42, "y": 42}},
 "dist_gem_pmt": 186,
 "pmt_radius": 11,
 "quantum_efficiency": 0.26,
 "pmt_time_response": {"transit_time": 17,
                       "transit_time_spread": 0.9},
 "pmt_signal": {"amplitude": -0.0042,
                "amplitude_dispersion": 0.00148,
                "sigma": 0.53,
                "lambda": 0.81},
 "fast_window_len": 1024,
 "slow_window_len": 4000,
 "fast_freq": 750e6,
 "slow_freq": 250e6,
 "fast_noise_path": {"pmt_1": "pmt_simulation/noise_psd/fast_noise_ch1.npy",
                     "pmt_2": "pmt_simulation/noise_psd/fast_noise_ch2.npy",
                     "pmt_3": "pmt_simulation/noise_psd/fast_noise_ch3.npy",
                     "pmt_4": "pmt_simulation/noise_psd/fast_noise_ch4.npy"},
 "slow_noise_path": {"pmt_1": "pmt_simulation/noise_psd/slow_noise_ch1.npy",
                     "pmt_2": "pmt_simulation/noise_psd/slow_noise_ch2.npy",
                     "pmt_3": "pmt_simulation/noise_psd/slow_noise_ch3.npy",
                     "pmt_4": "pmt_simulation/noise_psd/slow_noise_ch4.npy"},
 "nJobs": -1,
 "digitizers": "Both"}
```

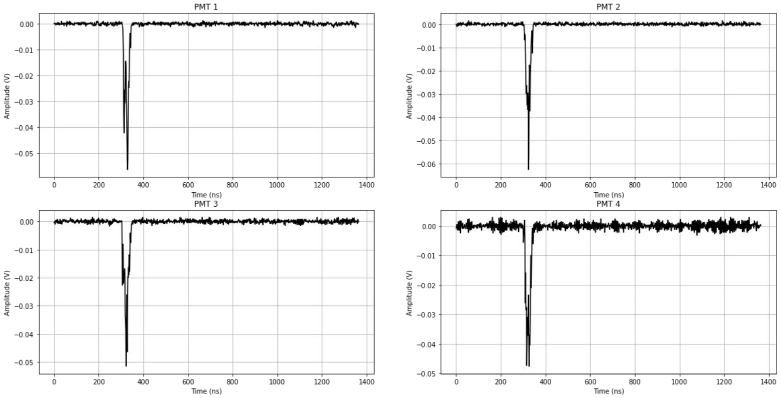
- Corrections in pmt positions
- New SPE signal parameters
- Fast and Slow digitizers parameters
- Path to noises PSDs
- Parallelization (in tests)
  - “nJobs”: Number of cores
  - Set -1 to use all cores available, maximum of 4
  - Set 1 to not use parallelization
- Digitizer selection
  - “digitizers”: “Both”, “Fast” or “Slow”

Code updates

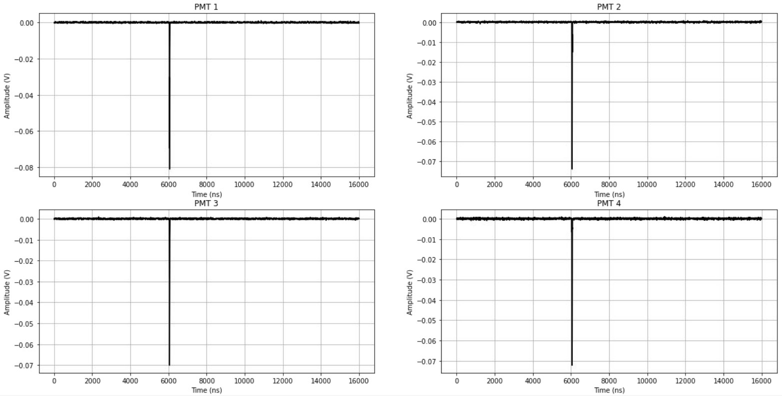
Example | Centered 6 kEV spot, z = 151 mm



Fast digitizer



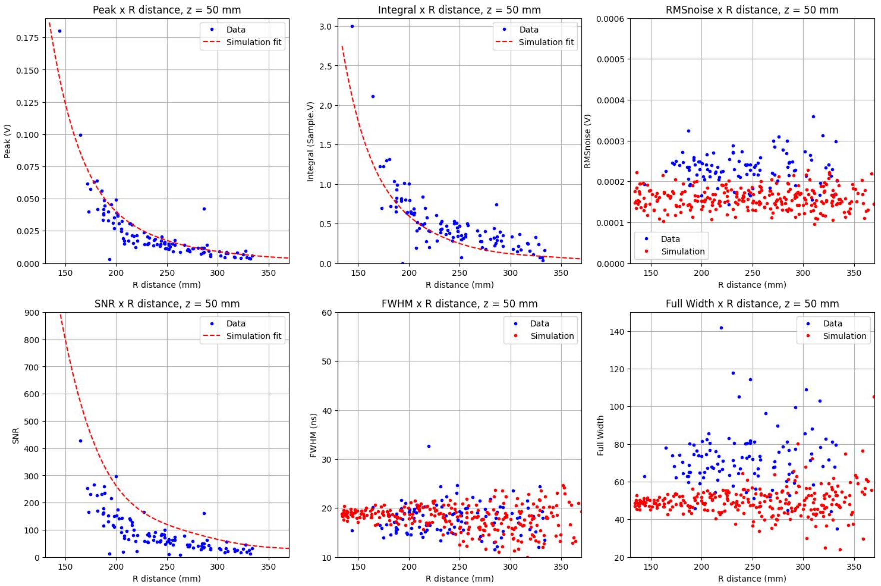
Slow digitizer



PMT Simulation took 0.4 seconds (without parallelization)

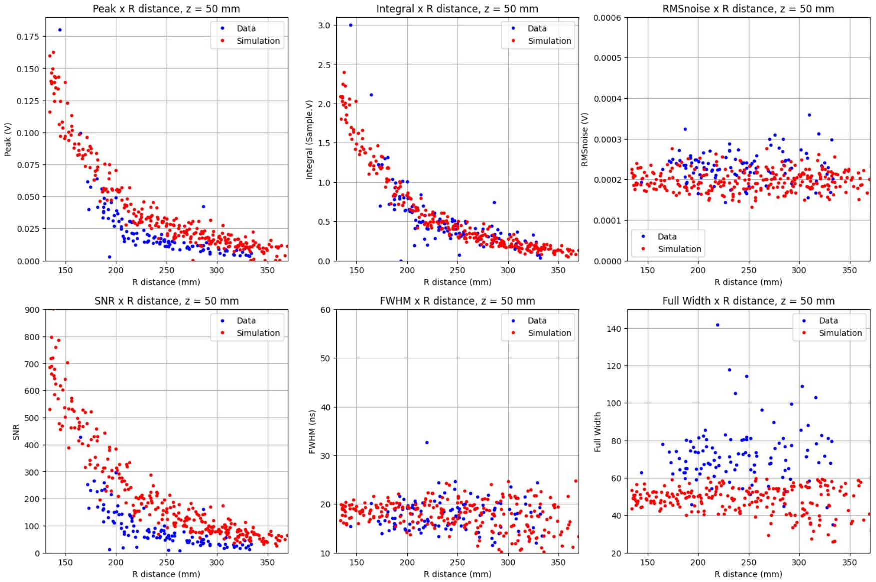
Code updates

From my last presentation



n = 3.9 in propagation equation

After new modifications



n = 4 in propagation equation

Conclusions

- The noise simulation is completed
  - 4 single channels simulations for each digitizer
- Fast/Slow digitizers and amplitude quantization completed
- SPE signal shape will not fix the tail of the PMT output shaping (voxels arrival ⟶ Gaussian?)

Next steps

- Simulate different tracks with different energies

Remember

- Latest updates in my fork (pmt-july24 branch):
  - https://github.com/luangmc/digitization/tree/pmt-july24