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Standalone XArapuca and 50L PMT Analysis

Introduction

- SP X-Arapuca
    - Noise
    - SPE
    - Deconvolution
    - Quartz/No window ratio
    - Model

- FLIC
    - Campaign 1,2,3, and 4

Trigger Noise

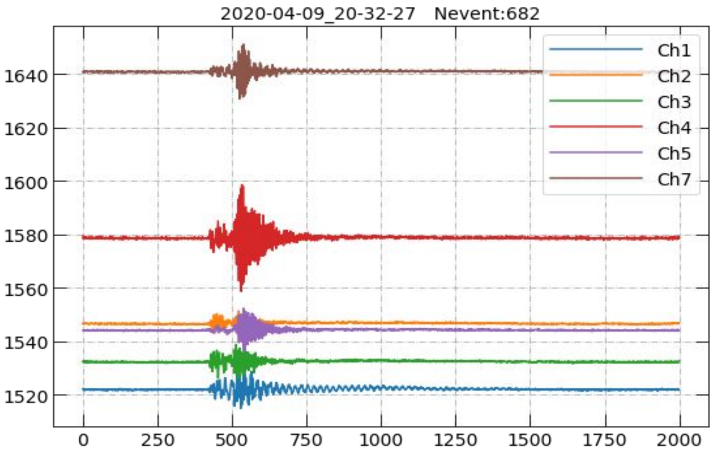


Figure 1: Averaged empty 682 events extracted from one runs. y-axis represent ADC count x-axis represent time tick in units of 6.7 nanosecond.

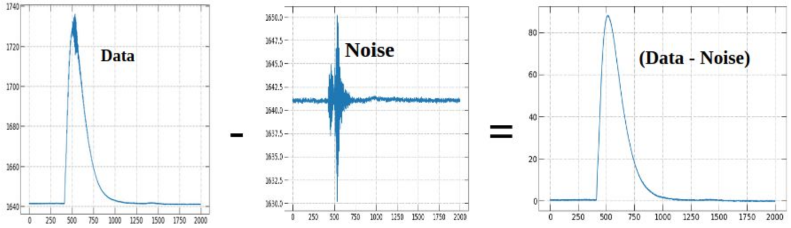


Figure 2: Removal of noise from data resulting denoised waveform.

- Event by event, each waveform is studied in detail, finding that about 7 % of the events are recorded without any particle signal. However, the noise is still presents in the waveforms.
- Later, these empty averaged events provide leverage to denoise the actual waveform. Additional benefit of denoising is correcting overshoot and undershoot of the signals.

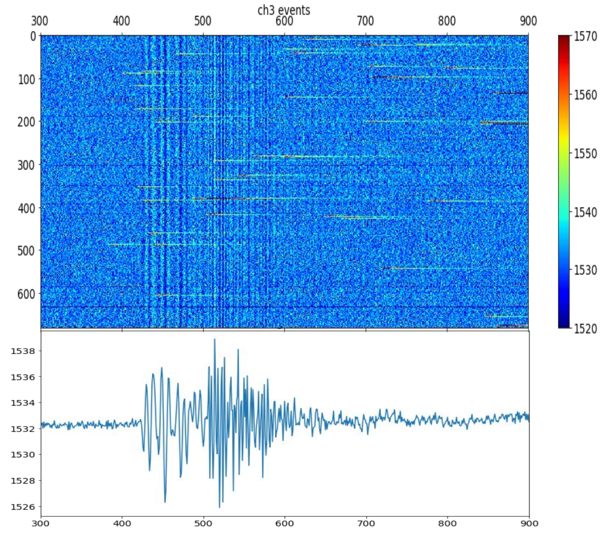
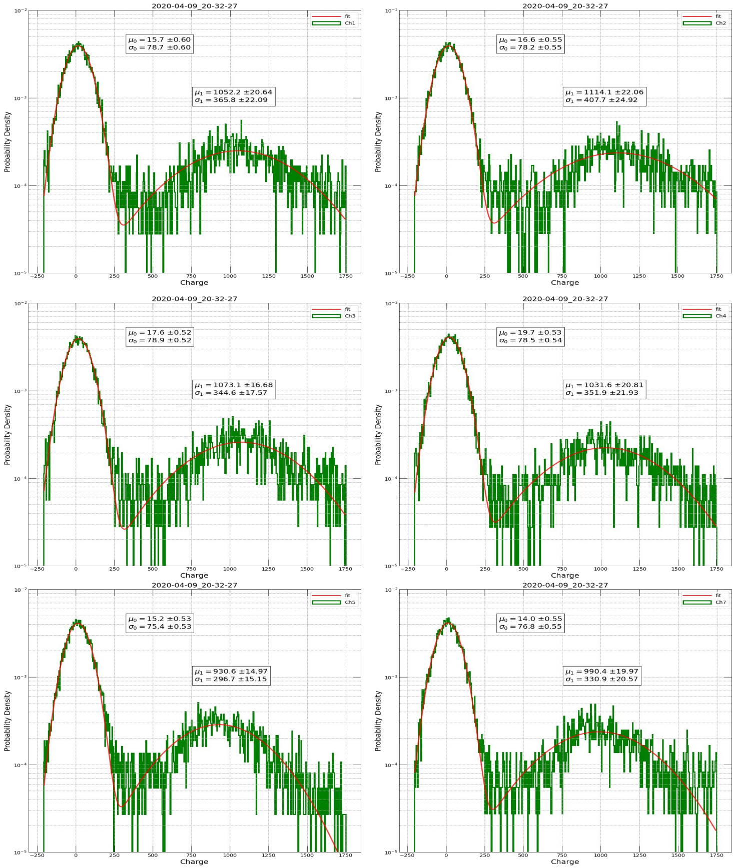
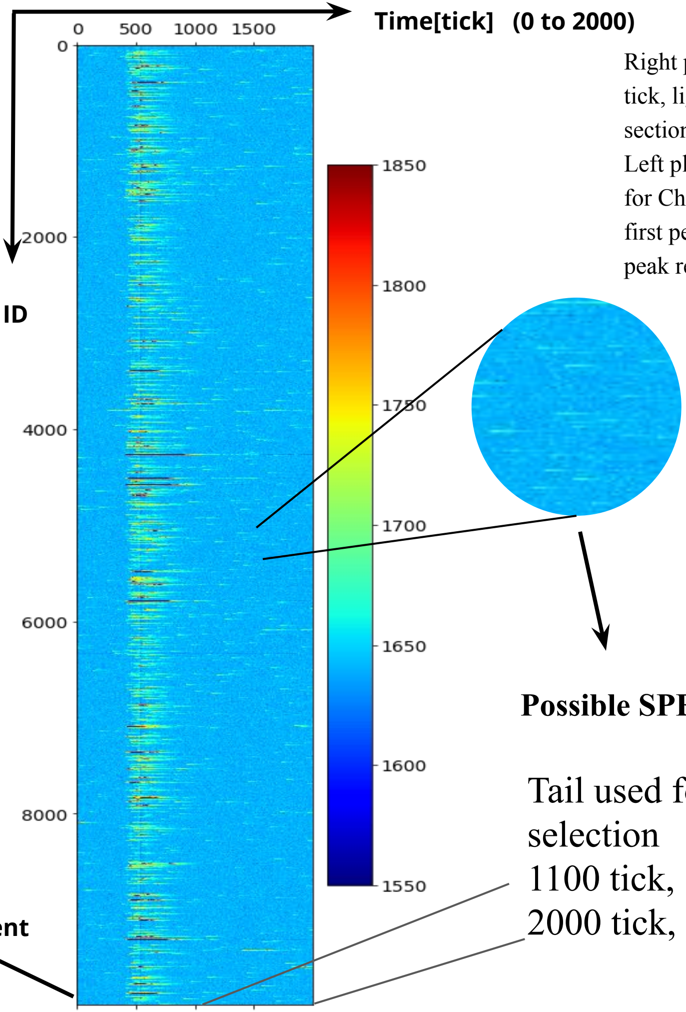


Figure 3: Noise

Single Photoelectron Spectra





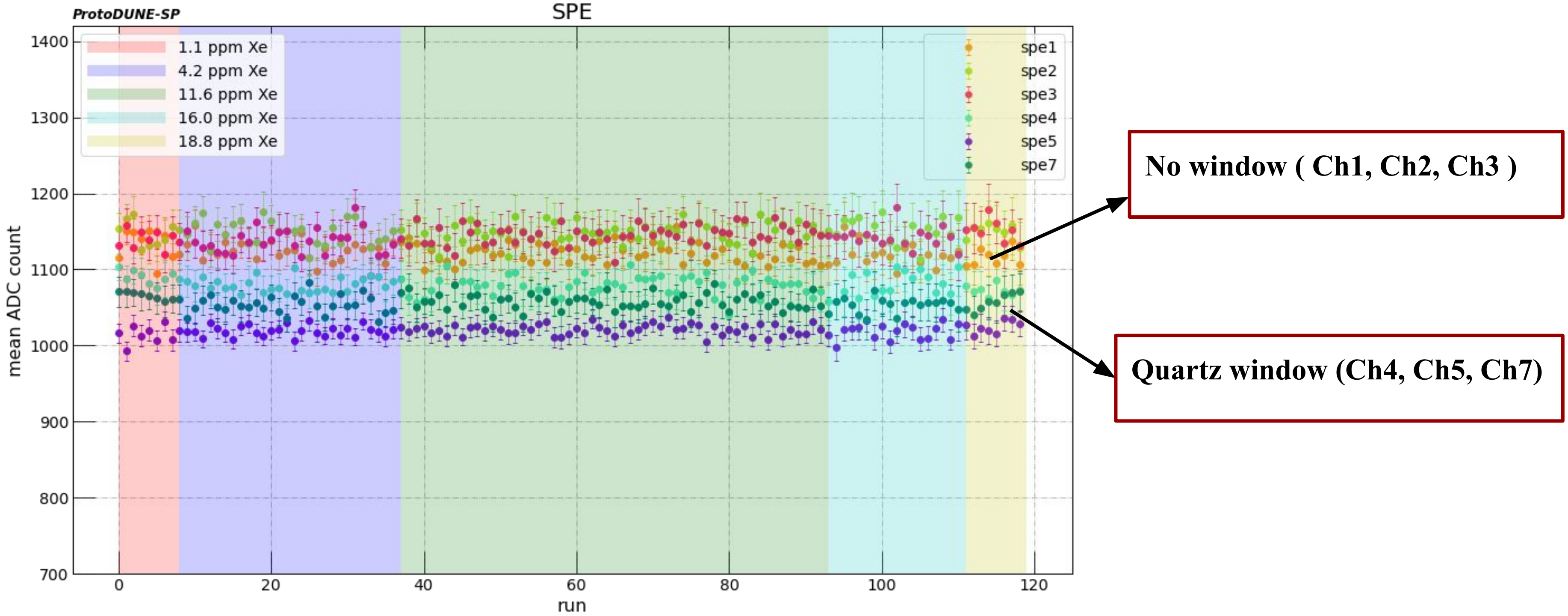
Right plot: x-axis event IDs and y-axis time tick, light green area trigger region, zoom in section shows possible SPE pulse candidate.

Left plots: Probability density versus charge for Ch5, double Gaussian function fitted, the first peak represents pedestal and second peak represent first SPE.

Possible SPEs

Tail used for SPE selection
1100 tick,
2000 tick,

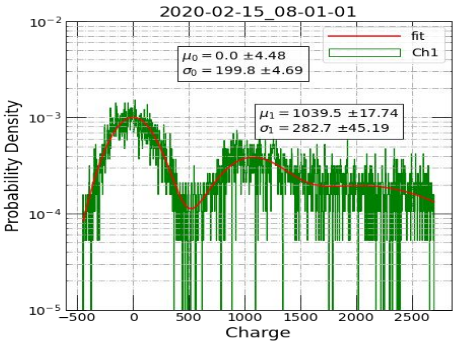
Stability SPE

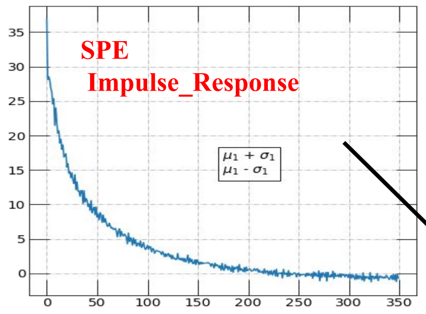


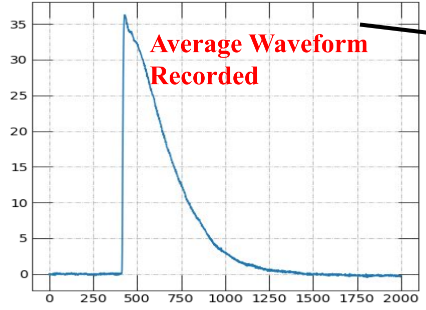
Mean SPE charge stability for all runs and each channel. Runs covers six-month time period!

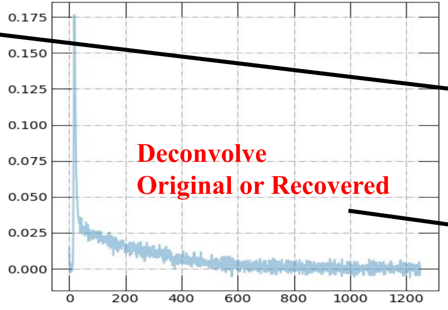
SPE waveform reconstruction, Deconvolution

SPE Spectra







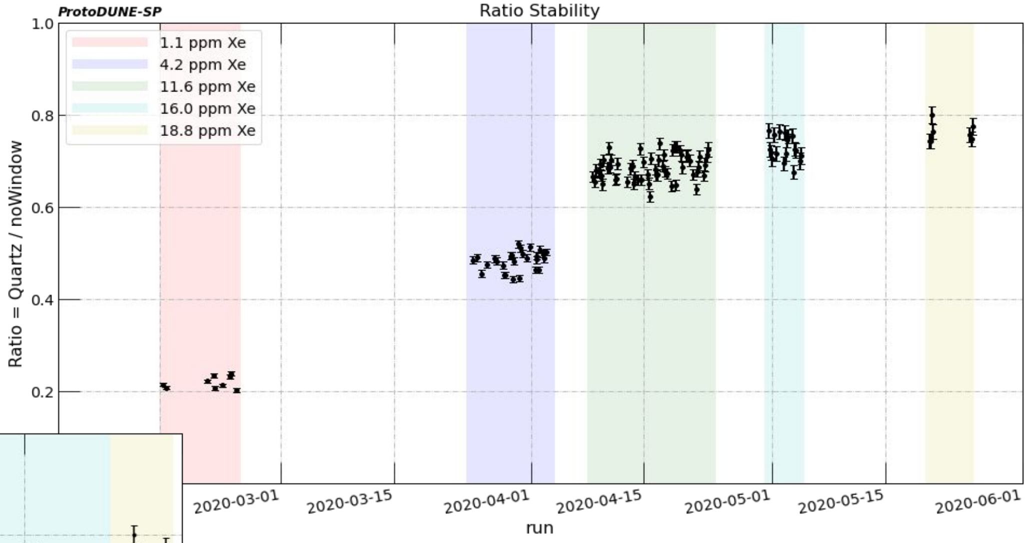


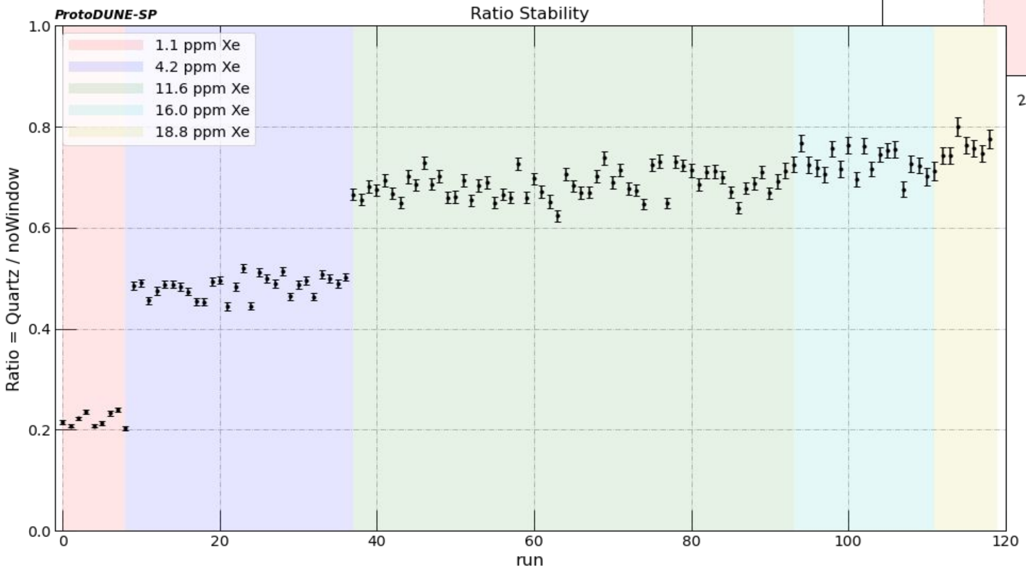
- SPE impulse response obtained by Gauss fit parameters
- Sigma and mean used as condition to make average SPE waveform
- Deconvolution …. scipy, same as matlab

```
>>> from scipy import signal
>>> original = [0, 1, 0, 0, 1, 1, 0, 0]
>>> impulse_response = [2, 1]
>>> recorded = signal.convolve(impulse_response, original)
>>> recorded
array([0, 2, 1, 0, 2, 3, 1, 0, 0])
```

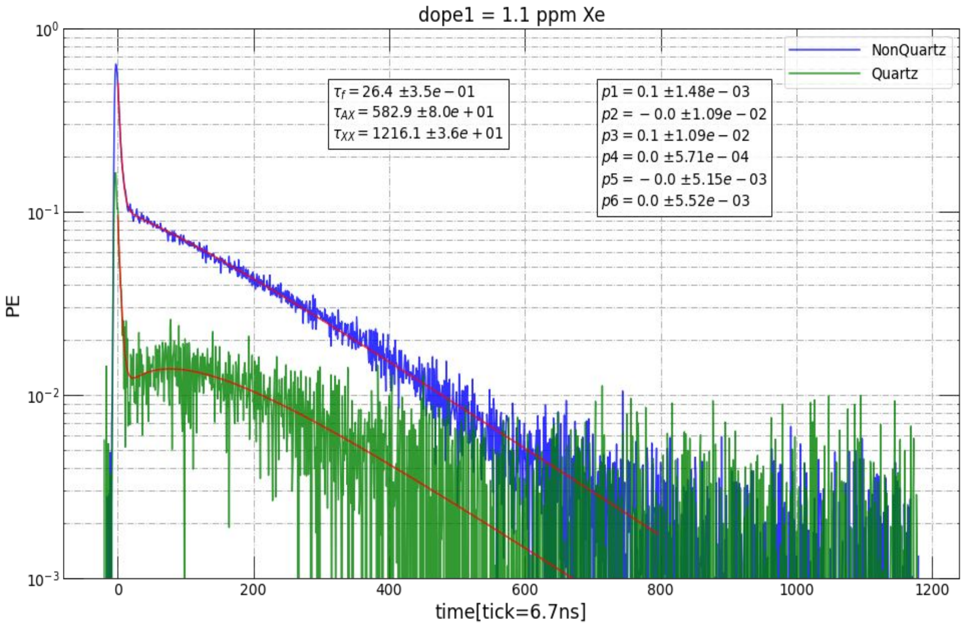
```
>>> recovered, remainder = signal.deconvolve(recorded, impulse_response)
>>> recovered
array([ 0.,  1.,  0.,  0.,  1.,  1.,  0.,  0.])
```

Ratio = Quartz / NoQuartz

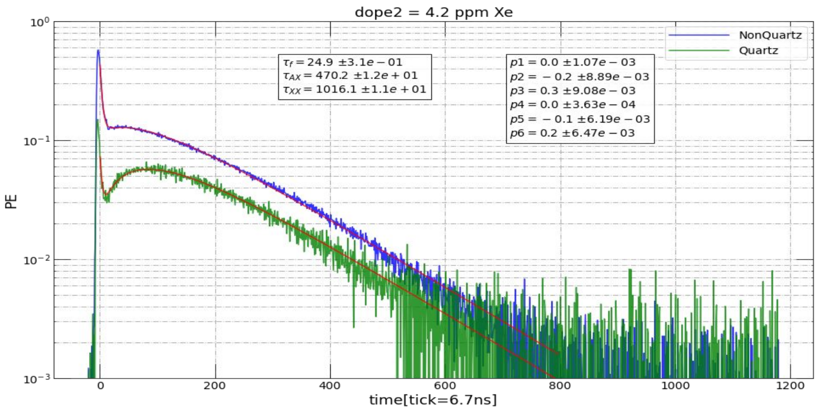


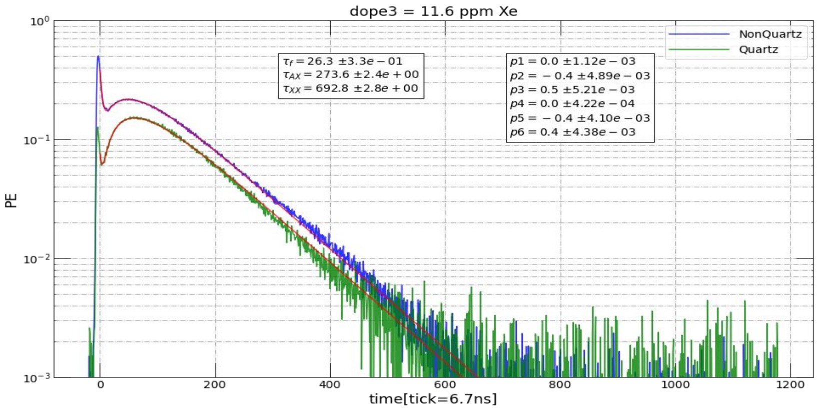


Average waveforms

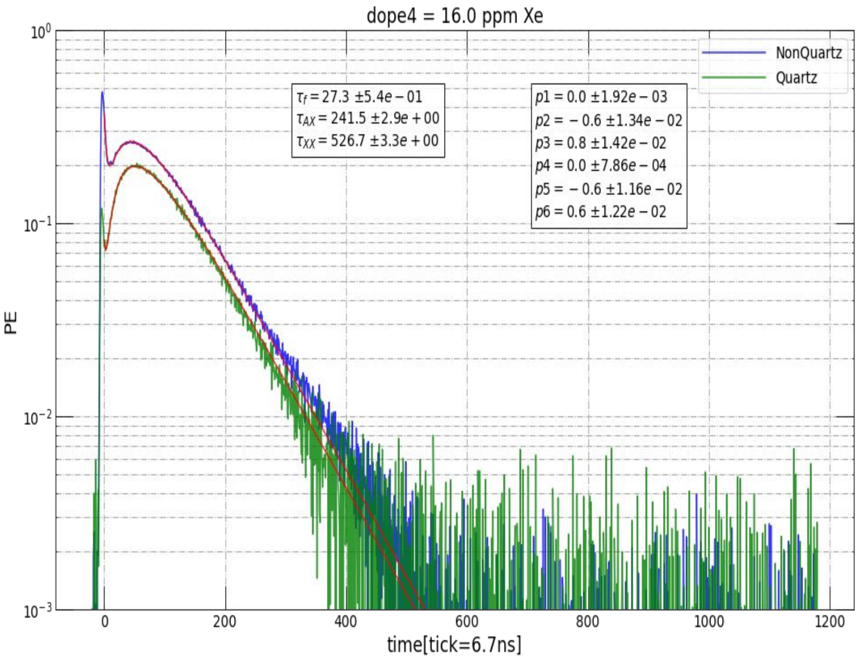


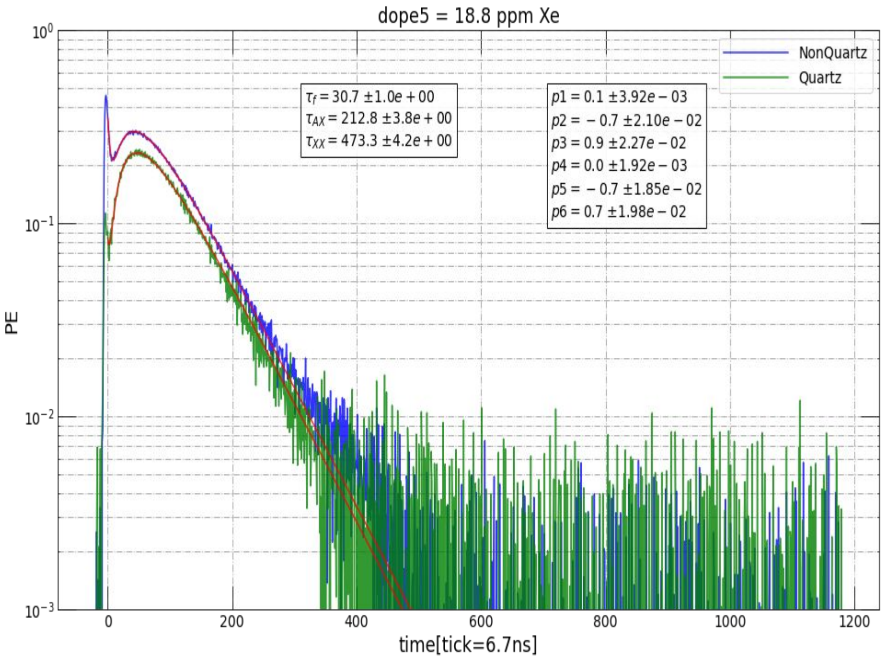
$$f = a * e^{-t/\tau_{Fast}} + b * e^{-t/\tau_{TA}} + c * e^{-t/\tau_{TX}}$$





Average waveforms





The quenching, the shifting and the scintillation

The ArAr * excited dimer (AA) disappears by scintillation (at 128 nm), quenching through nitrogen, and shifting to ArXe * (AX) through the process:

1) ArAr* + Xe -> ArXe* + Ar

$$\frac{dAA}{dt} = -\frac{AA}{\tau_{128}} - \frac{AA}{\tau_{N2}} - \frac{AA}{\tau_{AX}}$$

$$= -\frac{AA}{\tau_{TA}}$$

$$\frac{1}{\tau_{TA}} = \frac{1}{\tau_{128}} + \frac{1}{\tau_{N2}} + \frac{1}{\tau_{AX}}$$

The ArXe* dimer is formed from ArAr* dimer, can be destroyed by N2 and disappears through scintillation (at 150 nm) and shifting to XeXe* (XX) through the process :

2) ArXe* + Xe -> XeXe* + Ar

$$\frac{dAX}{dt} = +\frac{AA}{\tau_{AX}} - \frac{AX}{\tau_{150}} - \frac{AX}{\tau_{N2}} - \frac{AX}{\tau_{XX}}$$

$$= +\frac{AA}{\tau_{AX}} - \frac{AX}{\tau_{TX}}$$

$$\frac{1}{\tau_{TX}} = \frac{1}{\tau_{150}} + \frac{1}{\tau_{N2}} + \frac{1}{\tau_{XX}}$$

The XeXe * dimer is formed from the ArXe * dimer and disappears through scintillation (at 175 nm):

3) XeXe* -> Xe + Xe

$$\frac{dXX}{dt} = +\frac{AX}{\tau_{XX}} - \frac{XX}{\tau_{175}}$$

No window and Quartz scintillation

- **Non Quartz scint@ 128nm + 150nm + 178nm**

  The X-Arapuca without Quartz window (XN) will see the sum of the three spectra

$$\frac{dAA}{dt}(scint@128nm) = K\frac{\tau_{TA}}{\tau_{128}}\frac{e^{-t/\tau_{TA}}}{\tau_{TA}}$$

$$\frac{dAX}{dt}(scint@150nm) = K\frac{\tau_{TA}}{\tau_{150}}\frac{\tau_{TX}}{\tau_{AX}}\frac{(e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})}{(\tau_{TA} - \tau_{TX})}$$

$$\frac{dXX}{dt}(scint@175nm) = K\frac{\tau_{TA}}{\tau_{XX}}\frac{\tau_{TX}}{\tau_{AX}}\frac{(e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})}{(\tau_{TA} - \tau_{TX})}$$

$$\frac{dXN}{dt} = K\left[\frac{1}{\tau_{128}}\frac{e^{-t/\tau_{TA}}}{\tau_{TA}} + \left(\frac{\tau_{XX} + \tau_{150}}{\tau_{XX}\tau_{150}}\right)\left(\frac{\tau_{TA}\tau_{150}}{\tau_{AX}}\right)\frac{(e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})}{(\tau_{TA} - \tau_{TX})}\right]$$

- **Quartz scint@ 178nm**

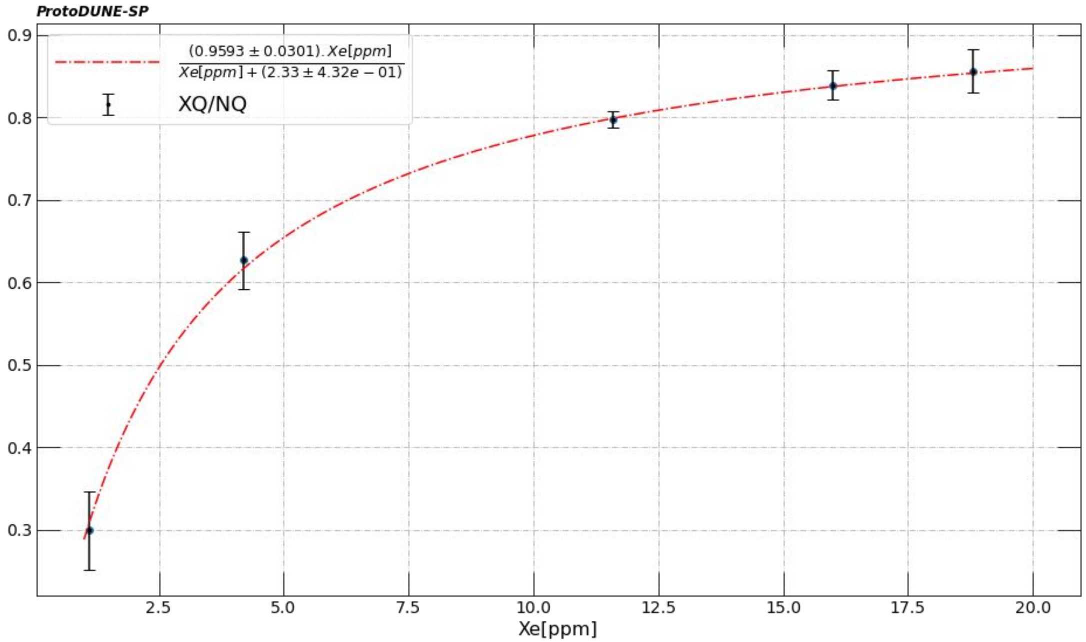
  The X-Arapuca with the Quartz window (XQ) will only be sensitive to the third spectrum (the one from XeXe*)

$$\frac{dXQ}{dt}(scint@175nm) = K\frac{1}{\tau_{XX}}\left(\frac{\tau_{TA}\tau_{150}}{\tau_{AX}}\right)\frac{(e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})}{(\tau_{TA} - \tau_{TX})}$$

- Ratio of **XQ/XN** would be intercalibration

$$\frac{XQ}{XN} = \frac{\tau_{150}}{\tau_{XX} + \tau_{150}}$$

XQ / XN Intercalibration



$$\frac{dXN}{dt} = K\left[\frac{1}{\tau_{128}}\frac{e^{-t/\tau_{TA}}}{\tau_{TA}} + \left(\frac{\tau_{XX}+\tau_{150}}{\tau_{XX}\tau_{150}}\right)\left(\frac{\tau_{TA}\tau_{150}}{\tau_{AX}}\right)\frac{(e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})}{(\tau_{TA}-\tau_{TX})}\right]$$

$$\frac{dXQ}{dt}(scint@175nm) = K\frac{1}{\tau_{XX}}\left(\frac{\tau_{TA}\tau_{150}}{\tau_{AX}}\right)\frac{(e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})}{(\tau_{TA}-\tau_{TX})}$$

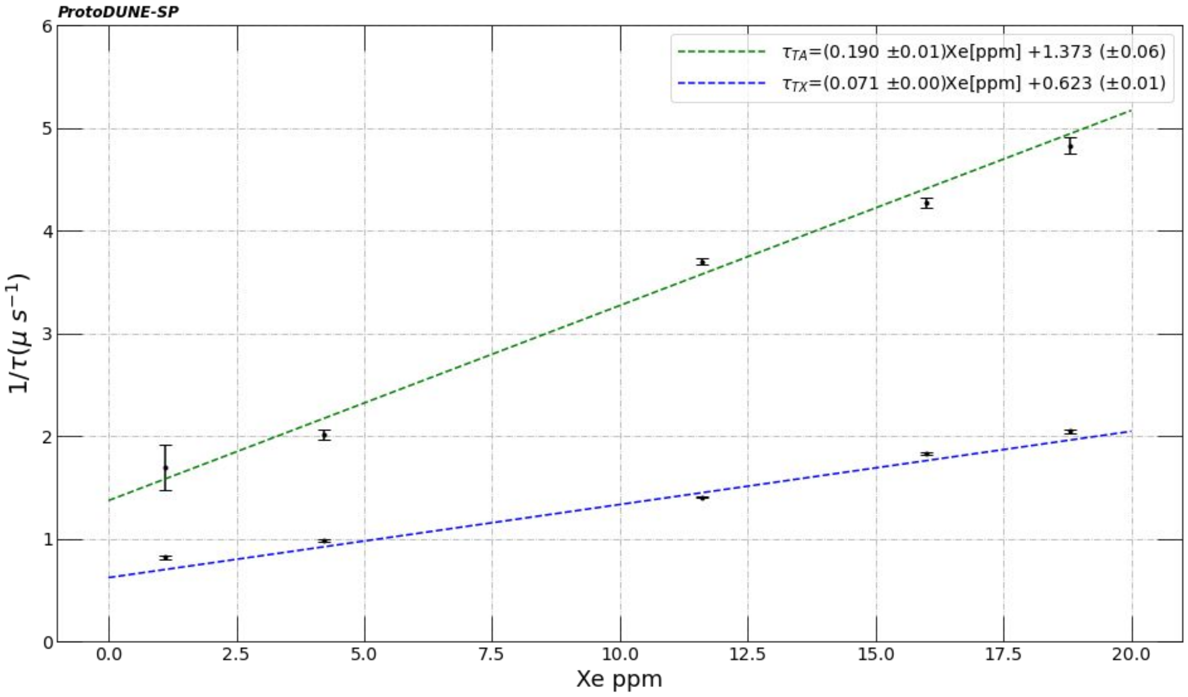
$$\frac{XQ}{XN} = \frac{\tau_{150}}{\tau_{XX}+\tau_{150}}$$

τ_{TA} and τ_{TX}

$$\frac{1}{\tau_{TA}} = \frac{1}{\tau_{128}} + \frac{1}{\tau_{N2}} + \frac{1}{\tau_{AX}}$$

constTA [1.373+/-0.062]
slopeTA [0.1898+/-0.005]

tau128 [1.469+/-0.7]
tauN2_TA [1.44 +/-0.689]

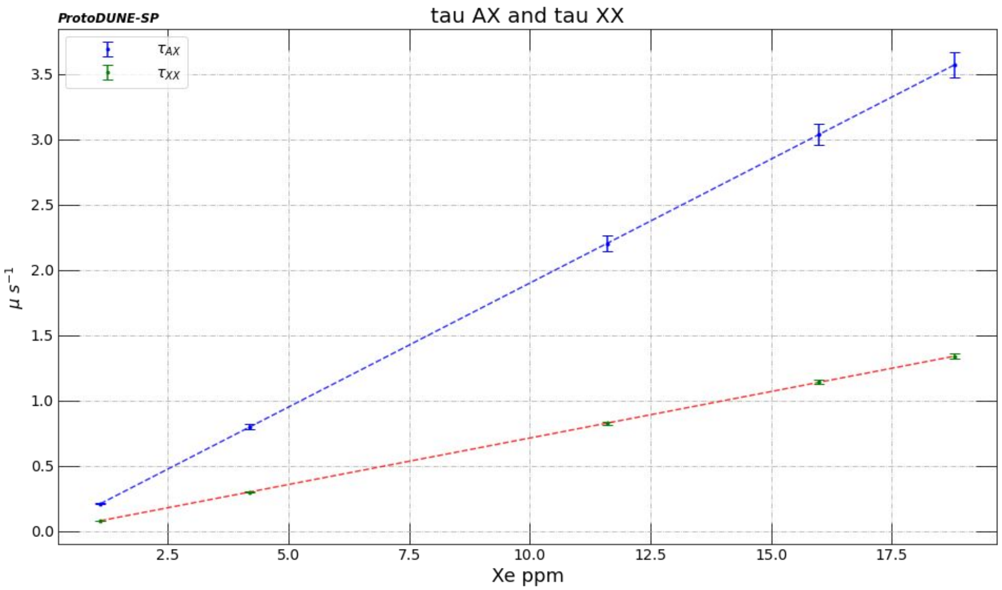


$$\frac{1}{\tau_{TX}} = \frac{1}{\tau_{150}} + \frac{1}{\tau_{N2}} + \frac{1}{\tau_{XX}}$$

constTX [0.62+/-0.01]
slopeTX [0.071+/-0.00]

τ_{AX} and τ_{XX}

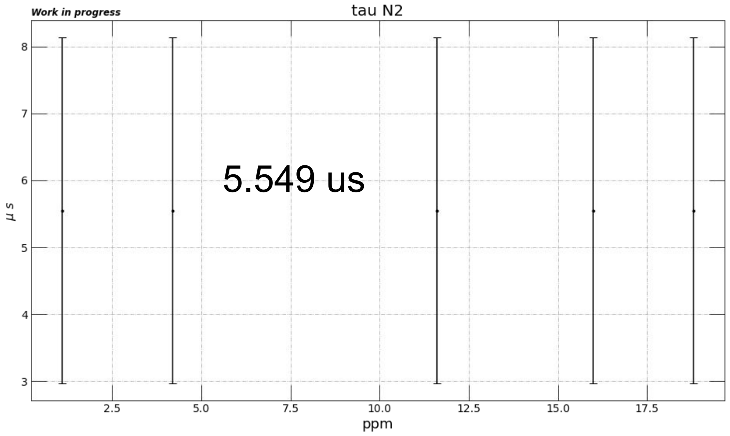
```
[[Fit Statistics]]
    # fitting method   = leastsq
    # function evals   = 7
    # data points      = 5
    # variables        = 2
    chi-square         = 1.5524e-17
    reduced chi-square = 5.1745e-18
    Akaike info crit   = -197.568027
    Bayesian info crit = -198.349151
[[Variables]]
    line_slope:       0.18984636 +/- 8.3352e-11 (0.00%) (init = 0.1)
    line_intercept:   1.9281e-09 +/- 1.0961e-09 (56.85%) (init = 0.208831)
[[Correlations]] (unreported correlations are < 0.100)
    C(line_slope, line_intercept) = -0.154
```

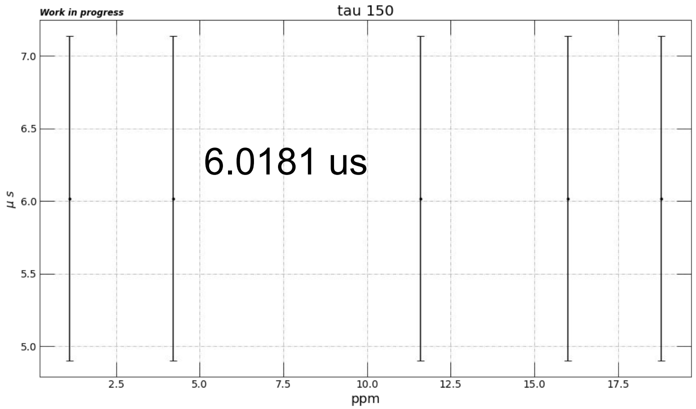



```
[[Fit Statistics]]
    # fitting method   = leastsq
    # function evals   = 7
    # data points      = 5
    # variables        = 2
    chi-square         = 6.5820e-19
    reduced chi-square = 2.1940e-19
    Akaike info crit   = -213.371061
    Bayesian info crit = -214.152185
[[Variables]]
    line_slope:       0.07118908 +/- 1.6972e-11 (0.00%) (init = 0.1)
    line_intercept:  -2.2975e-10 +/- 3.2674e-10 (142.22%) (init = 0.07830798)
```

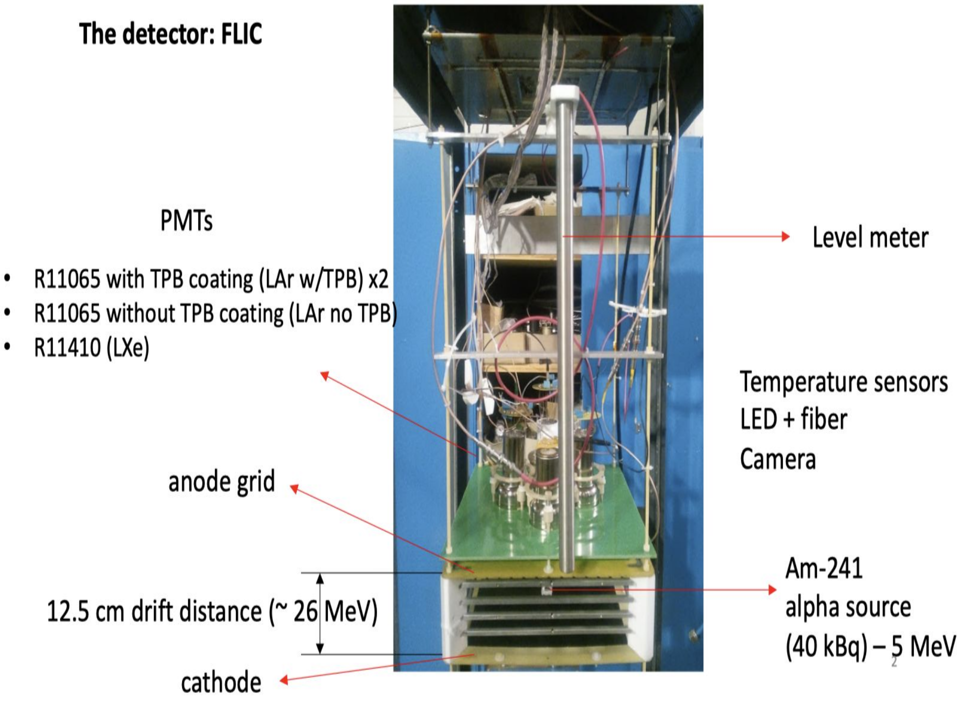
X-Arapuca parameters

	Xe	tau1	tau1_err	tau2	tau2_err	tau3	tau3_err	B	B_err	C	C_err	E	E_err	F	F_err
0	1.1	26.639656	0.343348	589.600000	76.327175	1220.084358	35.889695	-0.039487	0.012084	0.150273	0.012131	-0.033010	0.005783	0.044905	0.006186
1	4.2	24.908898	0.304308	495.566235	12.770620	1013.927046	12.169172	-0.203670	0.011749	0.335997	0.011960	-0.177235	0.008433	0.210476	0.008737
2	11.6	26.089766	0.319450	270.591131	2.211855	711.853997	2.583180	-0.414081	0.004451	0.569847	0.004751	-0.391590	0.003856	0.454254	0.004142
3	16.0	27.516472	0.540552	234.101137	2.638526	545.276810	3.000743	-0.635772	0.011007	0.803280	0.011759	-0.593354	0.009889	0.673964	0.010503
4	18.8	30.989320	0.989270	207.134409	3.431129	488.529817	3.804624	-0.763992	0.017556	0.930838	0.019334	-0.715407	0.016104	0.796928	0.017549





N2 -Xe Doping with FLIC



- The purpose of the test is to obtain the N2 contamination level in ProtoDUNE-SP by controlled doping of N2 and the level of Xe that should be doped to compensate for the light loss due to N2 impurity.

- Monitor the evolution of Xenon doping by studying the shape of the signal on various photon detection system before starting Xenon doping in ProtoDUNE-SP.

2nd Campaign / NitroXen

List of Runs

247,250,254,258,262,268,270,275,278,281,282,284,288,291,293,299,304,308,317,319,
323,325,327,332,336, 340

N2 Doping

-Run 258 started 1st N2 doping ~1h, 1ppm

-Run 268 started 2nd N2 doping ~2h, 2ppm

-Run 275 started 3rd N2 doping ~0.5 h, 0.5ppm

-Run 282 started 4th N2 doping ~0.5 h, 0.5ppm

-Run 288 started 5th N2 doping ~15 min, 0.25ppm

-Run 291 started 6th N2 doping ~24min, 0.4ppm

-Run 293 started 7th N2 doping ~24min, 0.4ppm

-Run 299 done with N2 doping at 5.2 ppm

Xe Doping

-Run 304 started 1st Xe doping ~1h, 20ppm

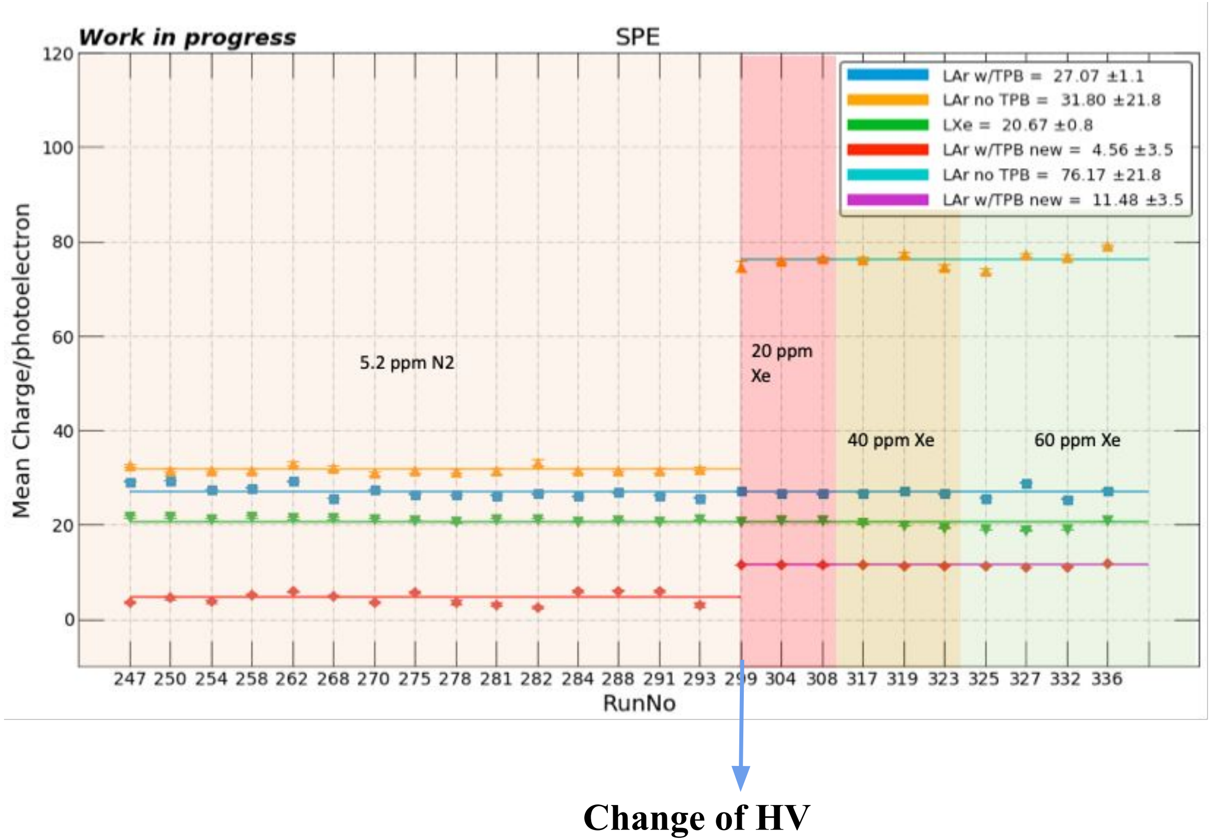
-Run 317 started 2nd Xe doping ~1h, 20ppm

-Run 325 started 3rd Xe doping ~1 h, 20ppm

-Run 340 another N2 doping started 1 ppm and increased 7.5 ppm

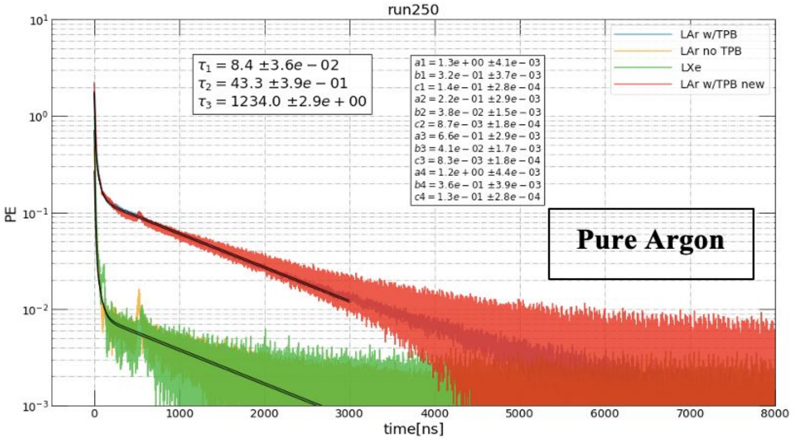
In total = 60 ppm Xe @ 12.7 ppm N2 injected

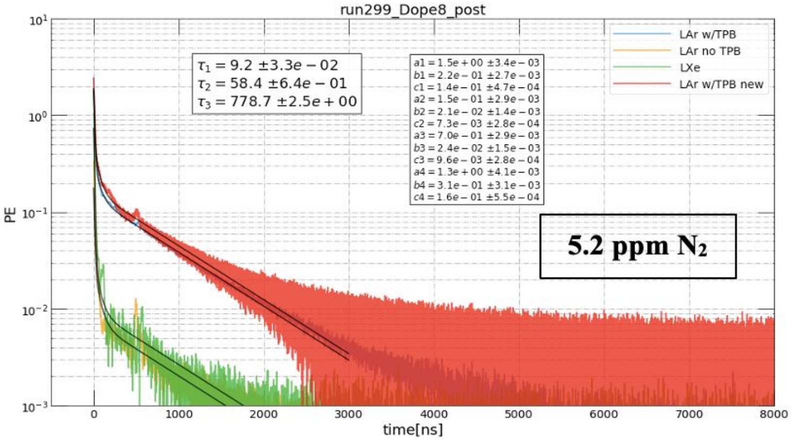
PMT Calibration

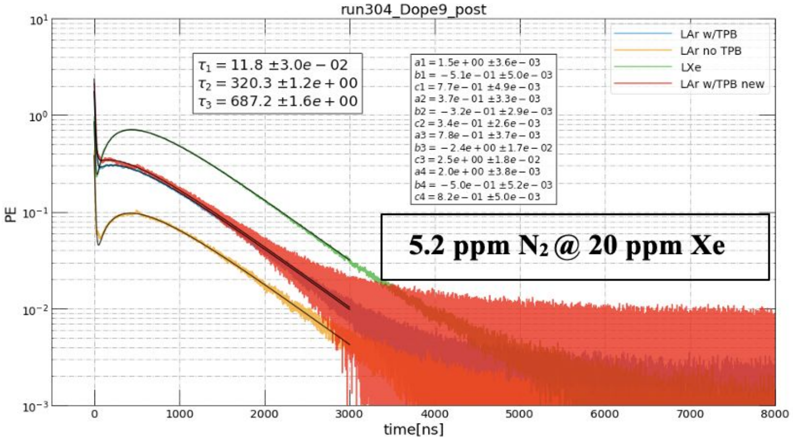


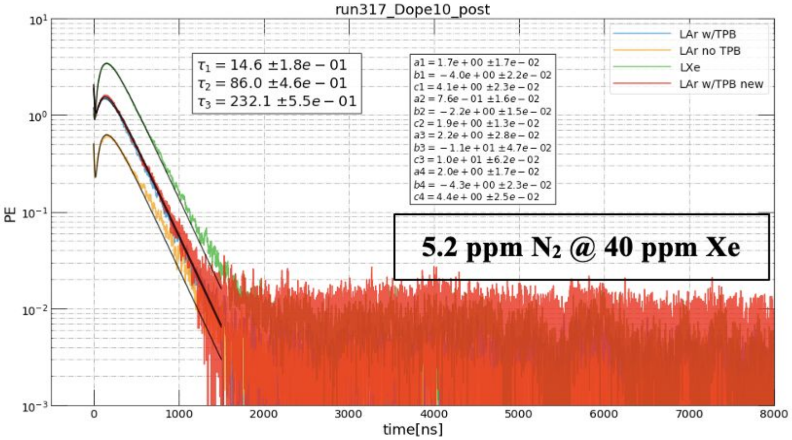
- Two TPB coated PMTs, one Xenon sensitive PMT (LXe) and one uncoated PMT.
- LAr no TPB and LAr w/TPB new have common HV which was increased from 1440V to 1550V, to obtain a higher gain for LAr w/TPB new at some point.

Average Waveforms with Simultaneous Fits for Each Doping



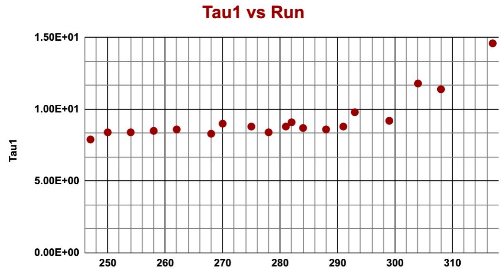


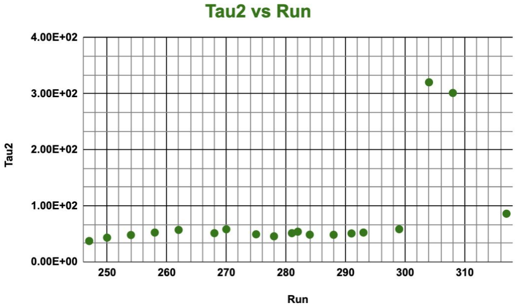


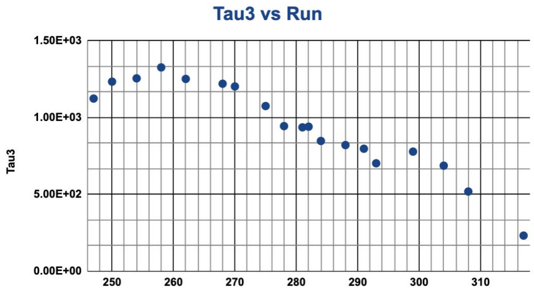


FLIC NitroXen Fit Parameters

Xenon	Nitrogen	Tau1	Tau1Err	Tau2	Tau2Err	Tau3	Tau3Err
0	0	7.90E+00	4.20E-02	3.73E+01	3.60E-01	1.12E+03	2.80E+00
0	0	8.40E+00	3.60E-02	4.33E+01	3.90E-01	1.23E+03	2.90E+00
0	0	8.40E+00	4.10E-02	4.80E+01	5.10E-01	1.26E+03	3.90E+00
0	1ppm	8.50E+00	5.10E-02	5.24E+01	6.70E-01	1.33E+03	5.90E+00
0	1ppm	8.60E+00	4.40E-02	5.71E+01	7.00E-01	1.25E+03	4.80E+00
0	3ppm	8.30E+00	4.60E-02	5.13E+01	6.00E-01	1.22E+03	4.40E+00
0	3ppm	9.00E+00	3.40E-02	5.82E+01	6.20E-01	1.20E+03	3.50E+00
0	3.5ppm	8.80E+00	5.10E-02	4.93E+01	6.80E-01	1.08E+03	4.20E+00
0	3.5ppm	8.40E+00	3.90E-02	4.57E+01	4.70E-01	9.45E+02	2.80E+00
0	3.5ppm	8.80E+00	4.20E-02	5.13E+01	6.20E-01	9.37E+02	3.30E+00
0	4ppm	9.10E+00	5.20E-02	5.39E+01	8.20E-01	9.41E+02	4.20E+00
0	4ppm	8.70E+00	4.60E-02	4.86E+01	6.30E-01	8.48E+02	3.30E+00
0	4.25ppm	8.60E+00	3.90E-02	4.84E+01	5.40E-01	8.21E+02	2.80E+00
0	4.65ppm	8.80E+00	3.80E-02	5.08E+01	5.80E-01	7.98E+02	2.90E+00
0	5.05ppm	9.80E+00	4.30E-02	5.24E+01	8.80E-01	7.03E+02	3.70E+00
0	5.2ppm	9.20E+00	3.30E-02	5.84E+01	6.40E-01	7.79E+02	2.50E+00
20ppm	5.2ppm	1.18E+01	3.00E-02	3.20E+02	1.20E+00	6.87E+02	1.60E+00
20ppm	5.2ppm	1.14E+01	2.80E-02	3.01E+02	9.00E-01	5.19E+02	1.20E+00
40ppm	5.2ppm	1.46E+01	1.80E-01	8.60E+01	4.60E-01	2.32E+02	5.50E-01

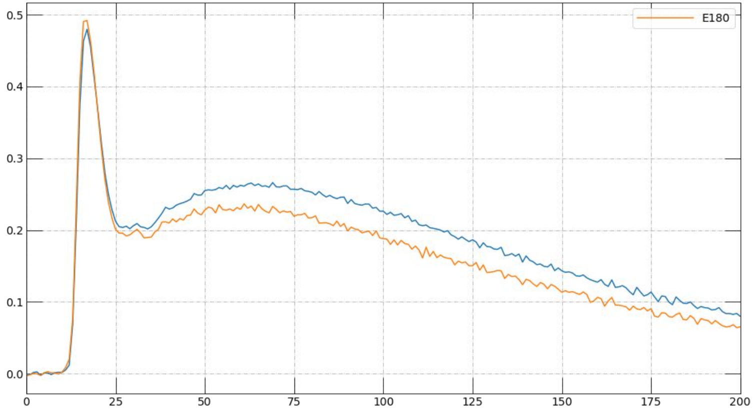






Sum

- X-Arapuca
  - SPE stability
  - Quartz/ noQuartz stability
  - Fit and model
  - Comparison S-Arapuca, DP, and Flic.

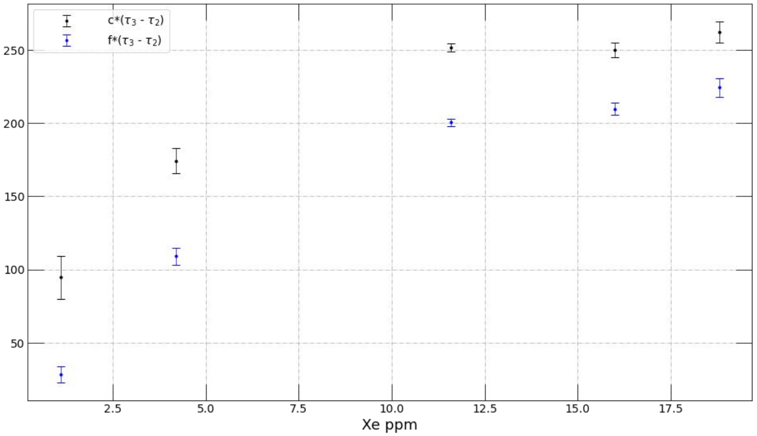


$$f = a * e^{-t/\tau_{Fast}} + b * e^{-t/\tau_{TA}} + c * e^{-t/\tau_{TX}}$$

$$f = \frac{\beta}{\tau_{TA}} * e^{-t/\tau_{TA}} + \frac{\gamma}{(\tau_{TA} - \tau_{TX})} * (e^{-t/\tau_{TA}} - e^{-t/\tau_{TX}})$$

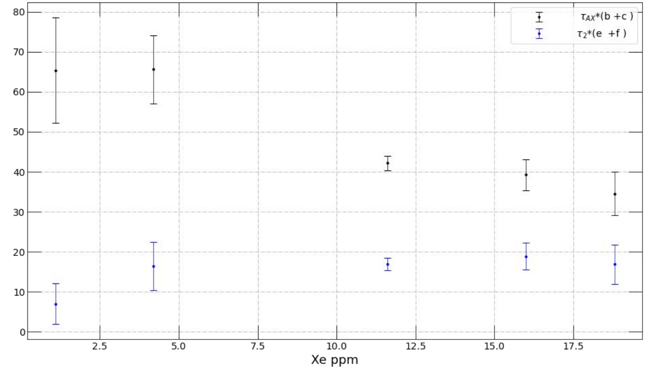
$$b = \frac{\beta}{\tau_{TA}} + \frac{\gamma}{\tau_{TA} - \tau_{TX}}$$

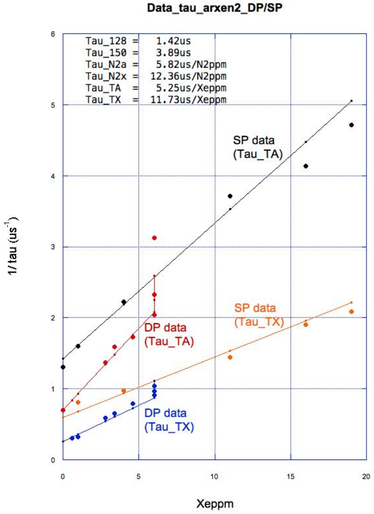
$$c = -\frac{\gamma}{\tau_{TA} - \tau_{TX}}$$



$$\beta = \tau_{TA} * (b + c)$$

$$\gamma = c * (\tau_{TX} + \tau_{TA})$$





50L IC Results