SPE and CA characterization with LED

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1 Motivation

The motivation for integrating an LED source within the cell is to facilitate simultaneous data collection for both Single Photon Events (SPE) and Alpha data while maintaining consistent conditions. Additionally, this setup aims to systematically enhance the statistics while streamlining the acquisition process for the necessary data.

This write-up aims to illustrate the conditions in which the LED source can produce the most optimal statistical data while addressing the inherent biases that may affect the measurement of correlated avalanches (CAs) in different media. In essence, I will demonstrate the application of a subtraction method for determining the average wave amplitude across various biases. This approach facilitates the calculation of CAs and ensures consistent results across different media.

2 Setup

The SPE data are taken in three different media: liquid Xenon (LXe), gaseous nitrogen (GN), and vacuum (VAC). The model of the function generator used is Keysight 33509B. The frequency is set to be less than or equal to 200 Hz with a 10% duty cycle using solicited-triggering.

For the SPE data obtained in GN and vacuum, LED wavelengths of 405nm and 310nm were used, while only a 405nm wavelength was used for SPE data collected in LXe due to time constraints (should I include the last part?).

3 Temperature Conditions

In the cell set-up, we used the silicon photomultiplier (SiPM) model, FBK VUV HD3, with an americium 241 source.

To showcase the variations in SiPM data induced by the different media, it is crucial to maintain consistent temperature levels, ensuring that temperature does not become a confounding factor.

During the liquefaction on July 13th/14th, the temperature data before July 14th were corrupted and lost due to a temporary disconnection of the hard drive. This includes the temperature data for LXe and GN, which will be discussed in this write-up.

LXe

To illustrate the consistency in temperature for the LXe 405 nm LED run, the mean temperatures at each bias are recorded in the metadata of the data files.

Finding the mean (μ) of those temperature values:

$$\begin{aligned}\mu &= \frac{x_1 + x_2 + x_3 + ... + x_N}{N} \\ &\approx 168.3599\text{K}\end{aligned}$$

To calculate the standard deviation of the mean:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$
$$= 0.00276 \approx 0.003\text{K}$$

Thus, the temperature during the LXe runs is quite stable at 168.360 ± 0.003K

GN

During the GN run, 1.5 bar of GN was injected into the cell. As mentioned before, the disconnection of the hard drive corrupted the temperature data for this run. However, it was recorded in the SiPM usage log to be at 171K during the beginning and end of the runs.

VAC

For the vacuum runs, the temperature profile during the 310 nm and 405 nm and LED runs were stored safely and shown below:

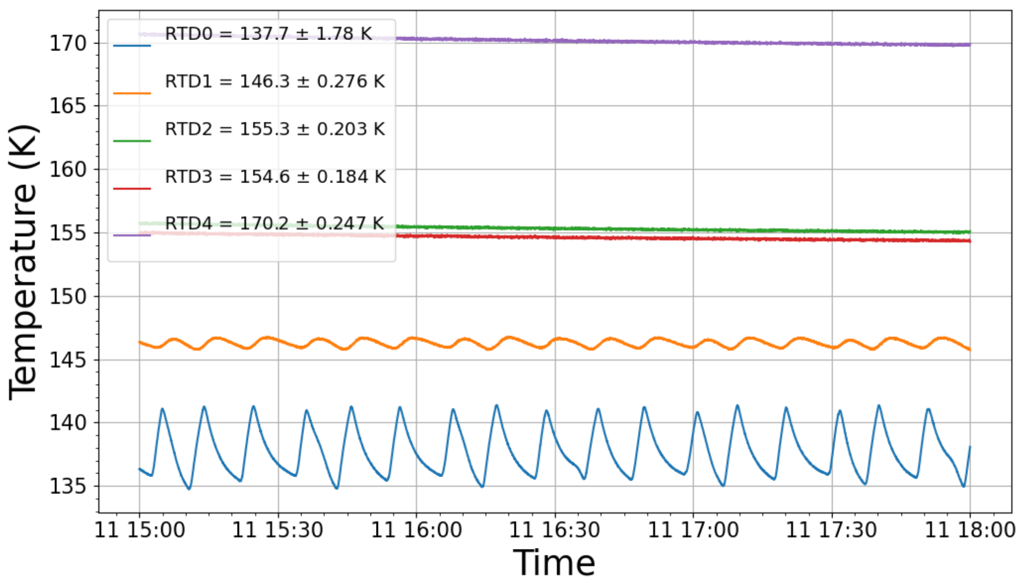

Figure 1: Temperature over the duration of 405nm LED SPE data acquisition. The legend shows the average and standard deviation of the temperature during the data collection.

The average temperature at the SiPM during data collection was 170.2 K with a standard deviation of $0.247 \approx 0.3$K over the course of 125 minutes. The starting temperature was 170.36K and ended at 169.84K, a total change of .52 K, which is within the uncertainty of the RTD sensors.

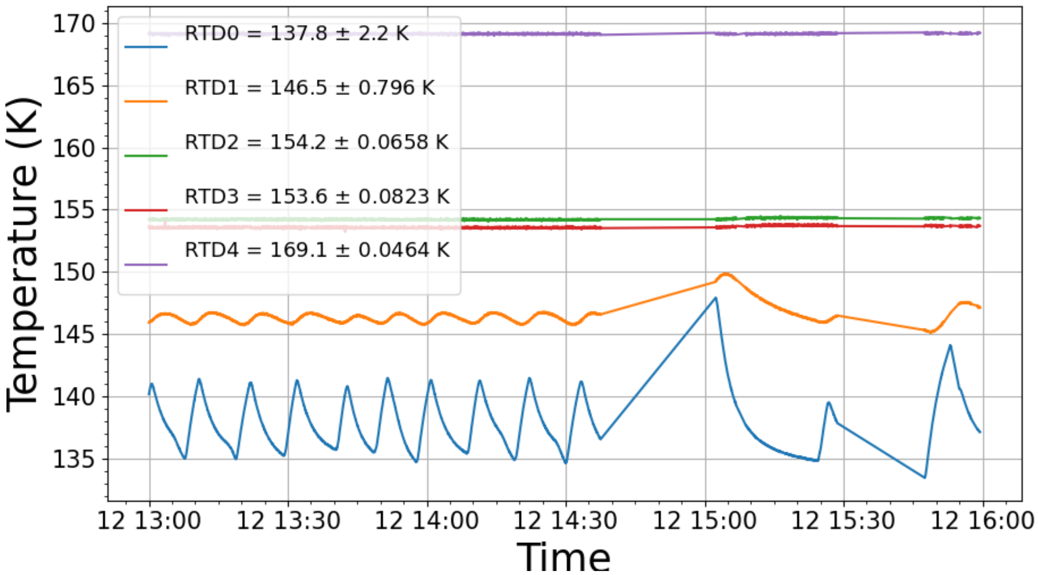

Figure 2: Temperature over the duration of 310nm LED SPE data acquisition. The legend shows the average and standard deviation of the temperature during the data collection.

The average temperature at the SiPM during data collection was 169.1 K with a standard deviation of $0.0464 \approx 0.05$K over the course of 103 minutes. The starting temperature was 169.09K and ended at 169.19K, a total change of .10 K, which is within the uncertainty of the RTD sensors.

4 LED Operating Conditions

In this section, I will present the optimal operating voltage for the LED in the different media. To find the optimal operating voltage, we consider two factors: the high ratio and the average amplitude of the waveforms.

The ratio of the LED is defined to be:

$$\frac{\text{Total num. of peaks detected (LED-on) - Total num. of peaks detected (LED-off)}}{\text{Total num. of peaks detected (LED-off)}}$$

To enhance the resolution of the SPE data peaks (where the p.e.'s are located), the LED strives to optimize their locations by enhancing the statistics. Therefore, a higher ratio is more optimal to distinguish the peak locations.

However, with too much increase in statistics, the average amplitude can skew and affect the CA calculation. Thus, operating at a voltage where the ratio is maximized without the average amplitude changing would be the most optimal.

LXe

Temperature

For the July 13th LXe 405 nm LED operating voltage tests, the data was taken at a temperature similar to that of the liquefaction data. As mentioned before, the temperature plots cannot be produced due to the hard drive incident. To calculate the temperature and its uncertainty, I inspected the metadata.

Finding the mean (μ) of those temperature values:

$$\mu = \frac{x_1 + x_2 + x_3 + ... + x_N}{N}$$
$$\approx 167.914\text{K}$$

To calculate the standard deviation of the mean:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$
$$= 0.158 \approx 0.2\text{K}$$

Thus, the temperature during the operating voltage LXe runs are quite stable at 167.9 ± 0.2K. Compared to the temperature taken for SPE calculations, the temperatures are close ($\approx 0.2K$ off) but not within each other's uncertainty.

Inspecting Waveforms

The bias we decided to operate at (for the SiPM) is 35V, as we found that bias to be the best at distinguishing the peak locations at a reasonable over-voltage (OV). To illustrate the increased SPE statistics, I will show both the raw waveforms and the 2D waveform density plots:

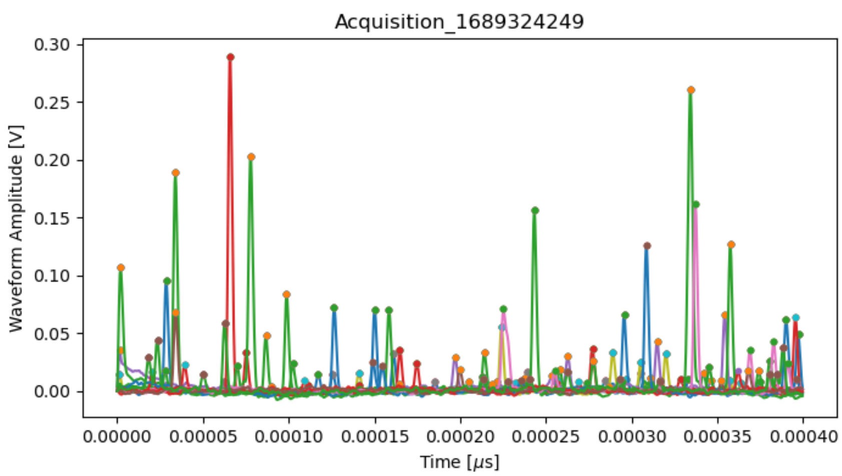

Figure 3: 100 raw waveforms using 405nm LED at 2.54V LED voltage with a low pass 400kHz low pass filter and double baseline correction (LXe).

The window is separated into two halves at the $2 \cdot 10^{-4}$s mark. The first half corresponds to the waveforms produced with the LED off, and the second half corresponds to the waveforms produced with the LED on. It is evident that there is an increase in detected peaks (the dots at each peak) statistics with the LED on.

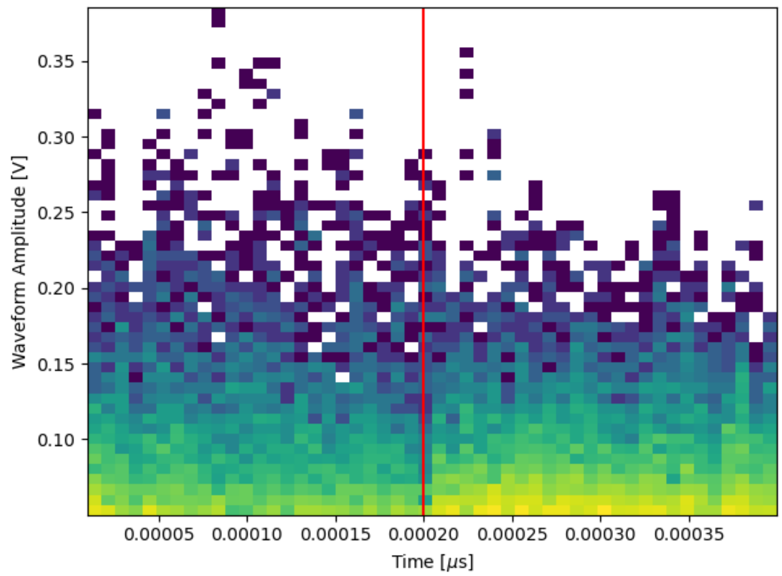

Figure 4: 2D waveform density plot using 405nm LED at 2.54V LED voltage with a low pass 400kHz low pass filter and double baseline correction (LXe).

If we look at the left-hand side (LED-off) versus the right-hand side (LED-on), it can be deduced by the denser yellow color at the bottom that there is an increase in statistics in SPE data.

Looking at the waveform plots, intuitively, the higher the LED voltage, the higher the ratio and the more distinguishable the peak locations are. However, as we increased the operating voltage, we noticed an increase in average amplitude at higher operating regions.

Average Amplitude and Ratio Analysis

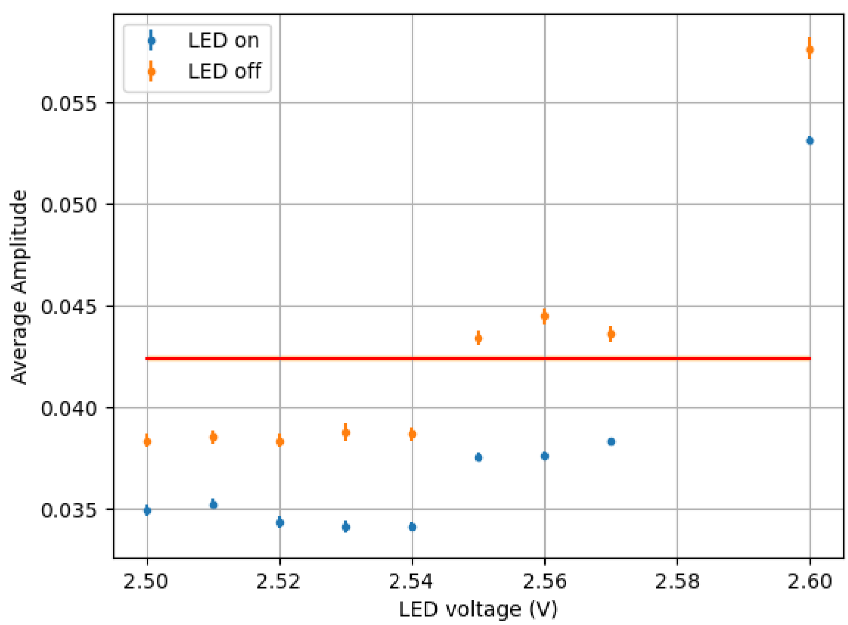

Figure 5: Average waveform amplitude vs LED voltage (405nm) at 35V bias (LXe).

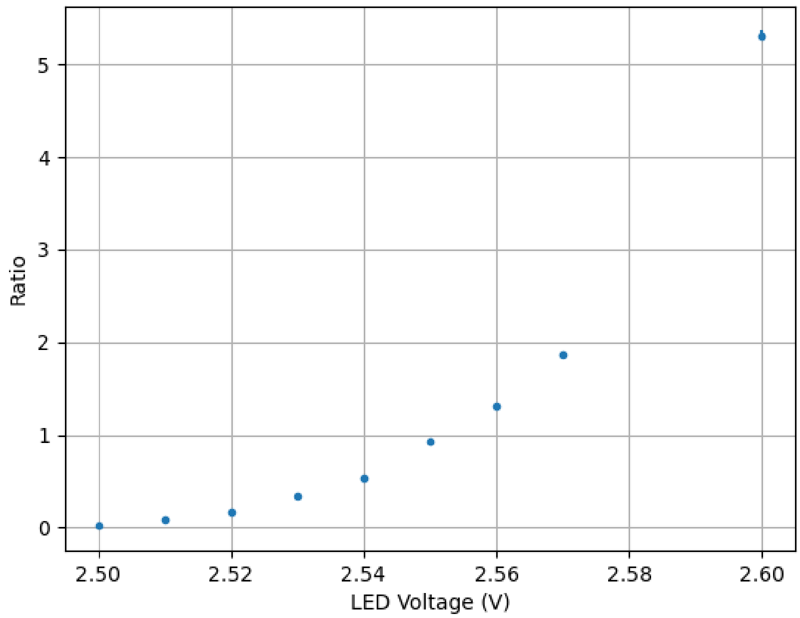

Figure 6: Ratio vs LED voltage (405nm) at 35V bias (LXe).

The conditions in which each average data point is acquired are the same as in Figure 3. In Figure 5, the orange horizontal line is the mean of the average amplitude when the LED is off (0.0425 ± 0.0001V). The purpose of the LED is to enhance the statistics while keeping the distribution the same, so the selected LED voltage needs to be in a region where the LED-on is close to the LED-off mean while maximizing the ratio (Figure 6).

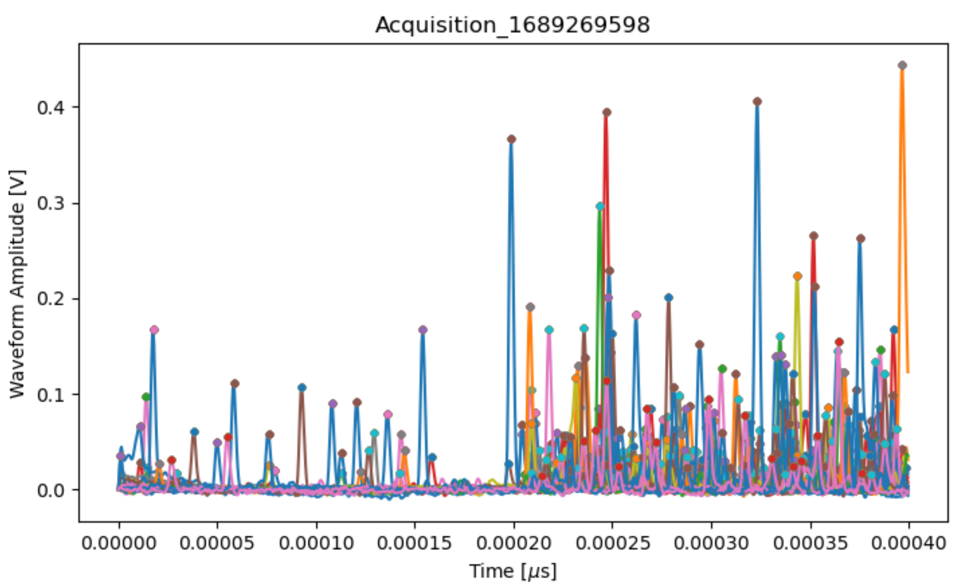

Figure 7: 100 raw waveforms using 405nm LED at 2.6V LED voltage with a low pass 400kHz low pass filter and double baseline correction (LXe).

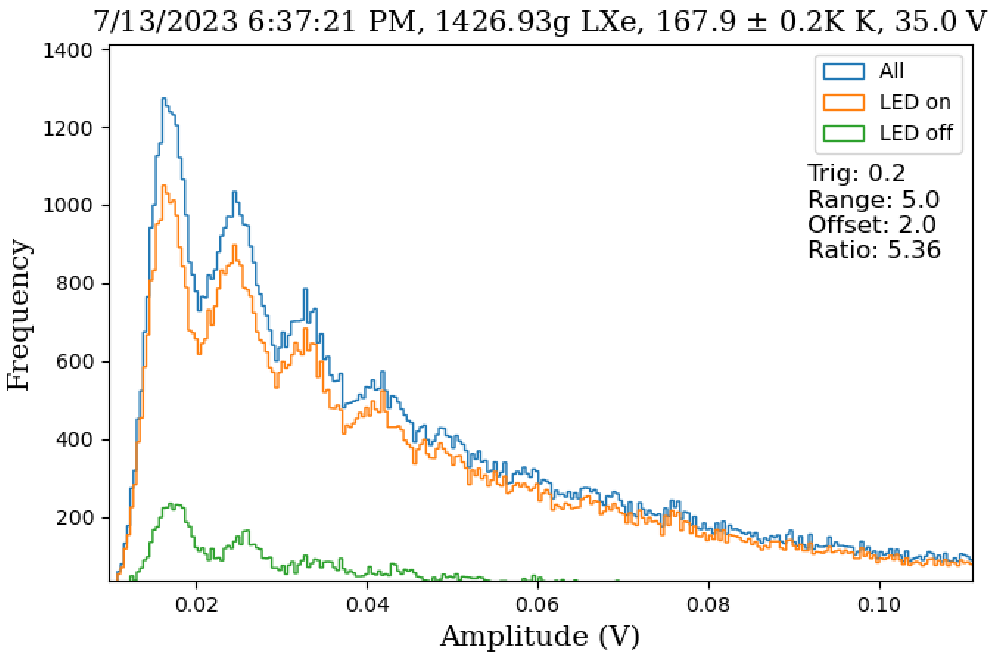

Figure 8: LED histogram using 405nm LED at 2.6V LED voltage with a low pass 400kHz filter and double baseline correction (LXe).

In Figure 7 and Figure 8, the increased statistics and distinguished peak locations due to higher ratios are evident. However, by looking at the average amplitude for 2.6V LED voltage ($\approx$ 0.055V), the average is a lot higher than the average amplitude mean for LED-off.

We also noticed that all the average amplitude data points in Figure 5 are higher than when in vacuum ($\approx$ 0.025V), which led us to believe that there is an overall increase in scintillation in liquid Xenon from the radioactive decay and cosmic rays. If we look at the raw waveform data (Figure 3 & Figure 7), there are a lot more large pulses in both the LED-on and LED-off window compared to in vacuum (Figure 28).

Histogram Subtraction Method (LED-Only)

To account for this extra scintillation, we devised a histogram subtraction method. Let the counts of each bin in the subtracted histogram be S_i and the counts for each bin in LED-on and LED-off histograms be $n_i \pm \sqrt{n_i}$ and $m_i \pm \sqrt{m_i}$, respectively:

$$S_i = n_i - m_i$$
$$\Delta S_i = \sqrt{n_i + m_i}$$

To find the mean ($\bar{x}$) of the histogram, let $\mathbb{S}_i$ be the normalized histogram counts at each bin and x_i to be the amplitude value at the center of each bin:

$$
\begin{aligned}
\mathbb{S}_i &= \frac{S_i}{\sum_{i=1}^{\#\text{bins}} S_i} (\text{normalized histogram counts}) \\
\bar{x} &= \sum_{i=1}^{\#\text{bins}} \mathbb{S}_i \cdot x_i \\
&= \frac{\sum_{i=1}^{\#\text{bins}} S_i \cdot x_i}{\sum_{i=1}^{\#\text{bins}} S_i}
\end{aligned}
$$

To find the uncertainty on the mean ($\Delta \bar{x}$):

$$
\begin{aligned}
\Delta \bar{x}^2 &= \sum_{i=1}^{\#\text{bins}} \left(\frac{\partial \bar{x}}{\partial S_i} \right)^2 \Delta S_i^2 \\
&= \sum_{j=1}^{\#\text{bins}} \left(\frac{\sum_{i=1}^{\#\text{bins}} (S_i x_i) - x_j \sum_{i=1}^{\#\text{bins}} S_i}{(\sum_{i=1}^{\#\text{bins}} S_i)^2} \right)^2 (n_j + m_j) \\
\Delta \bar{x} &= \sqrt{\sum_{j=1}^{\#\text{bins}} \left(\frac{\sum_{i=1}^{\#\text{bins}} (S_i x_i) - x_j \sum_{i=1}^{\#\text{bins}} S_i}{(\sum_{i=1}^{\#\text{bins}} S_i)^2} \right)^2 (n_j + m_j)}
\end{aligned}
$$

Using the subtraction method, the calculated mean value accounts for the extra scintillation in LXe:

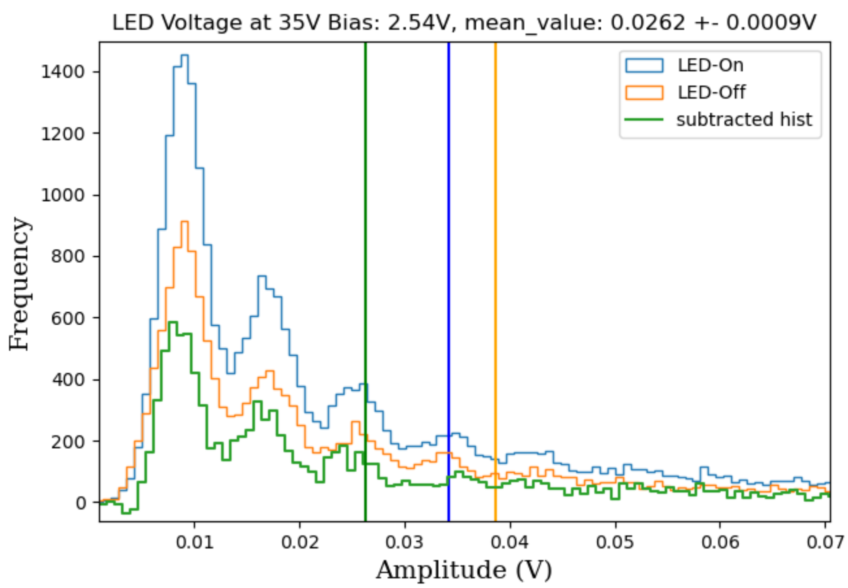

Figure 9: LED subtracted histogram using 405nm LED at 2.54V LED voltage with a low pass 400kHz low pass filter and double baseline correction (LXe).

In Figure 9, the green histogram represents the subtracted histogram or the LED-only histogram. By calculating the mean of the subtracted histogram, the mean is ”corrected” as the value matches the average amplitude in a vacuum under the same conditions (Figure), around 0.026 $\pm$0.0009V.

Using the same approach for the different LED operating voltage:

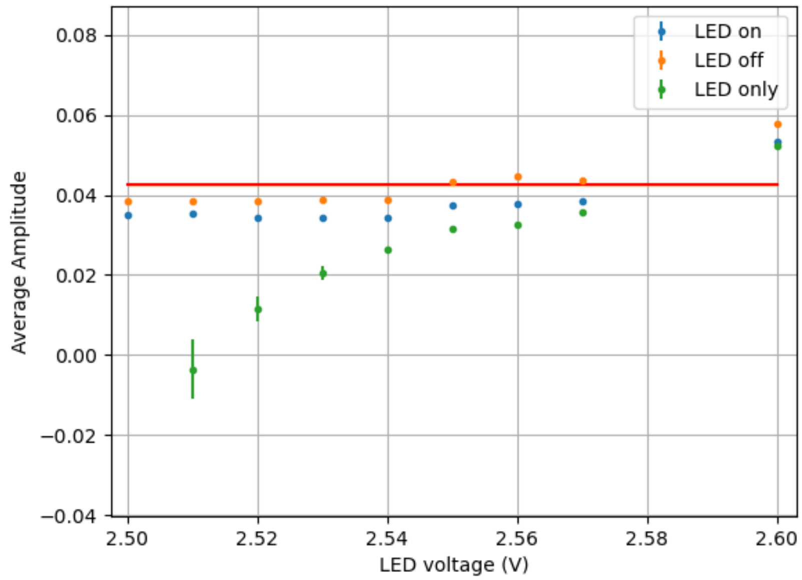

Figure 10: Average waveform amplitude vs LED voltage (405nm) at 35V bias with LED-only (LXe).

Looking at Figure 10, 2.54V is the most optimal LED operating voltage. The value satisfies the conditions by providing an average amplitude that avoids skewing the CA and a ratio high enough to enhance SPE statistics effectively.

GN

Temperature

For the July 11th/12th GN 310nm/405nm LED operating voltage tests, the data was taken at a temperature similar to that of the liquefaction data. As mentioned before, the temperature plots cannot be produced due to the hard drive incident. To calculate the temperature and its uncertainty, I inspected the metadata.

Finding the mean (μ) of those temperature values:

$$\mu = \frac{x_1 + x_2 + x_3 + ... + x_N}{N}$$
$$\approx 171.365\text{K}$$

To calculate the standard deviation of the mean:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$
$$= 0.01227 \approx 0.01\text{K}$$

Thus, the temperature during the GN runs is quite stable at 171.37 ± 0.01K.

Average Amplitude and Ratio Analysis

To see if the histogram subtraction method works and performs correctly in GN, we have to show that the LED-only average amplitude is similar to that of the LED-off average amplitude. The LED-off average in GN has been tested and experimented to be $\approx$ 0.026V. Using the exact same function generator, we found the average amplitude and ratio at different LED voltages for the 310 nm and 405 nm LED. Additionally, for enhanced time efficiency, we disabled the 400kHz low pass filter, given the already distinctive peaks at 35V.

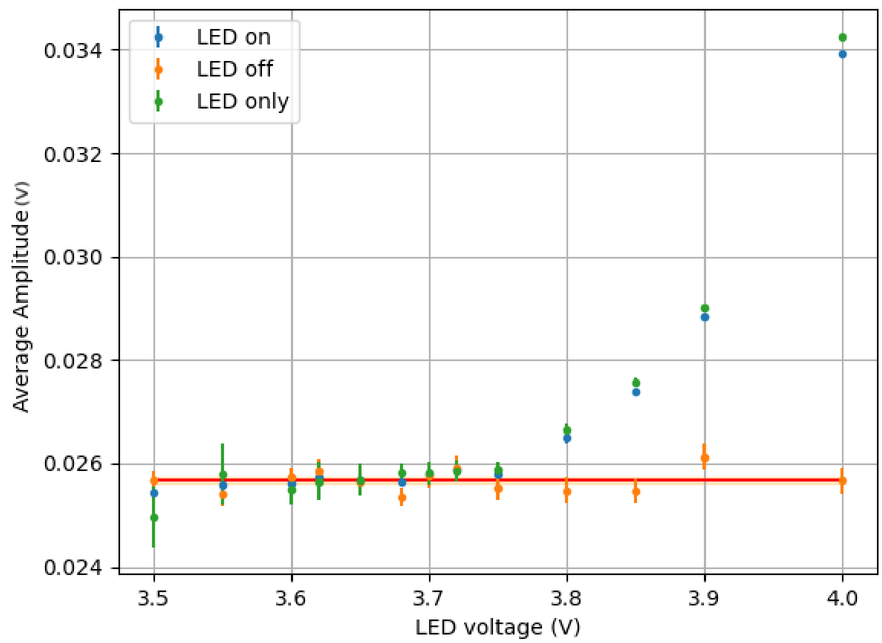

Figure 11: Average waveform amplitude vs LED voltage (310nm) at 35V bias with LED-only (GN).

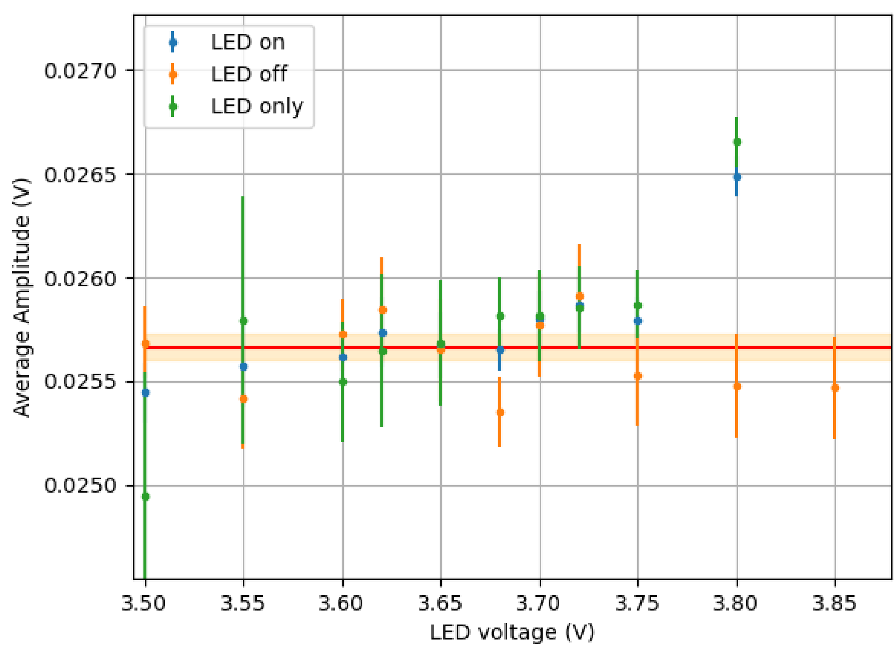

Figure 12: Zoomed average waveform amplitude vs LED voltage (310nm) at 35V bias with LED-only (GN)

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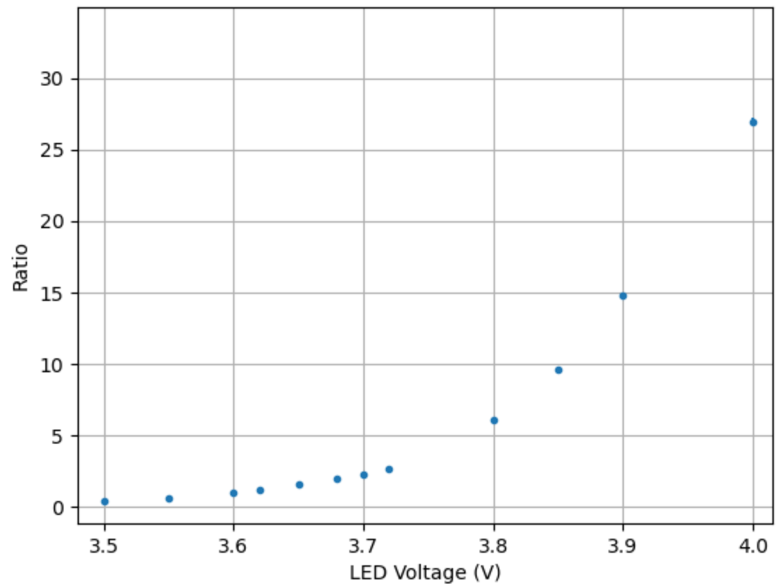


Figure 13: Ratio vs LED voltage (310nm) at 35 bias (GN).

When examining the LED-only data points, they exhibit similar behavior to those with LED-on at higher LED voltage levels, deviating from the anticipated average amplitude mean (0.02566 ± 0.00006V). In regions where there is no deviation ($\lesssim 3.75$V), all LED-only points and the average amplitude mean of LED-off fall within each other's uncertainty. This suggests that the histogram subtraction method can indeed accurately and consistently depict the correct average amplitude in LXe. Upon inspecting the ratio plot (Figure 12) and the zoomed amplitude plot (Figure 11), it is apparent that an operating voltage of 3.65V for a 310nm LED in GN yields an average amplitude close to the LED-off mean while achieving a ratio high enough to enhance SPE statistics notably.

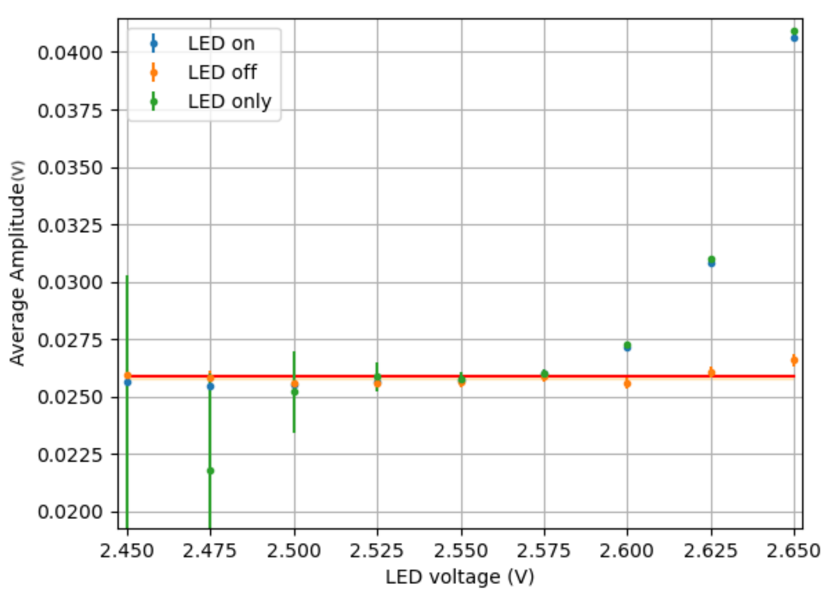


Figure 14: Average waveform amplitude vs LED voltage (405nm) at 35V bias with LED-only (GN).

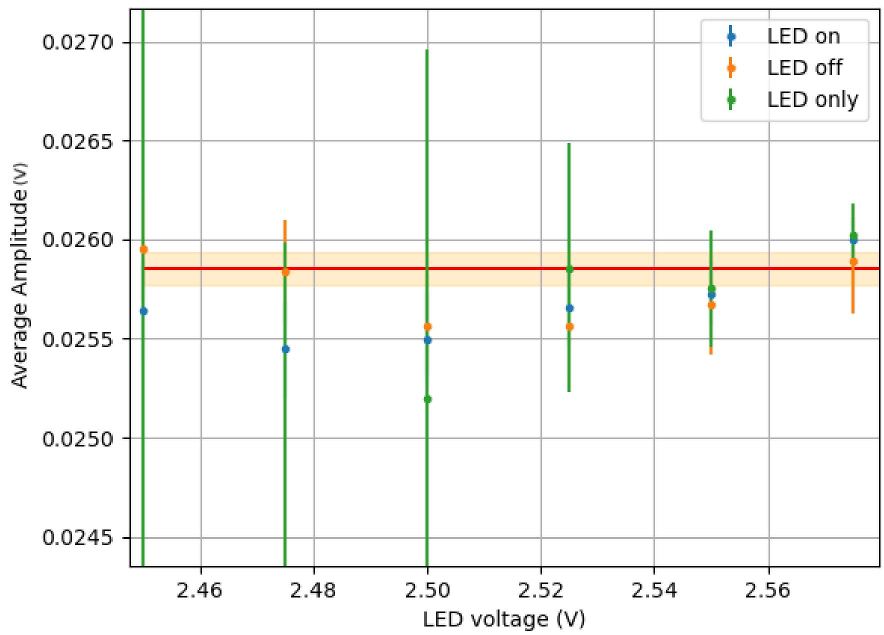


Figure 15: Zoomed average waveform amplitude vs LED voltage (405nm) at 35V bias with LED-only (GN).

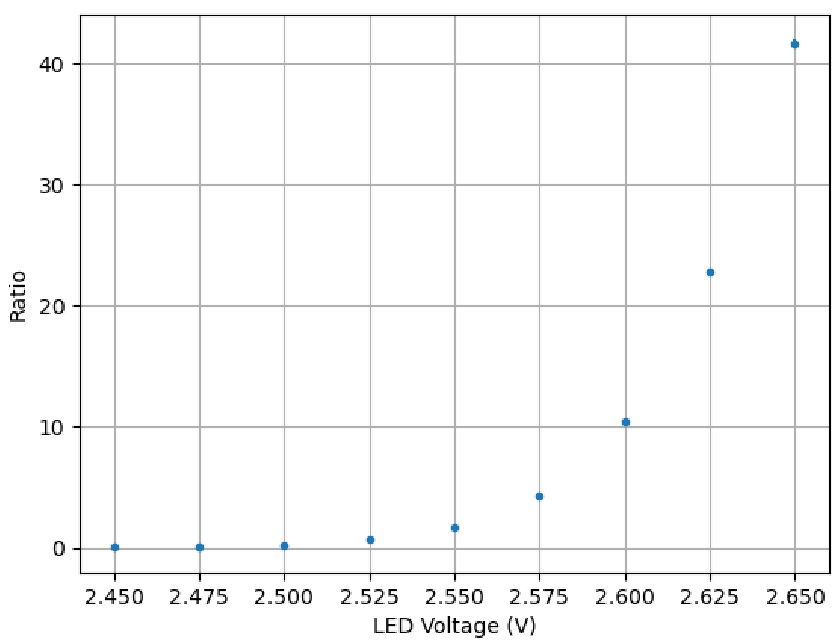


Figure 16: Ratio vs LED voltage (405nm) at 35 bias (GN).

Using a similar method to find the optimal operating voltage, looking at Figure 15 and Figure 16, 2.55V produces an average amplitude around the LED-off average amplitude mean (0.02585 ± 0.00009) while maximizing the ratio.

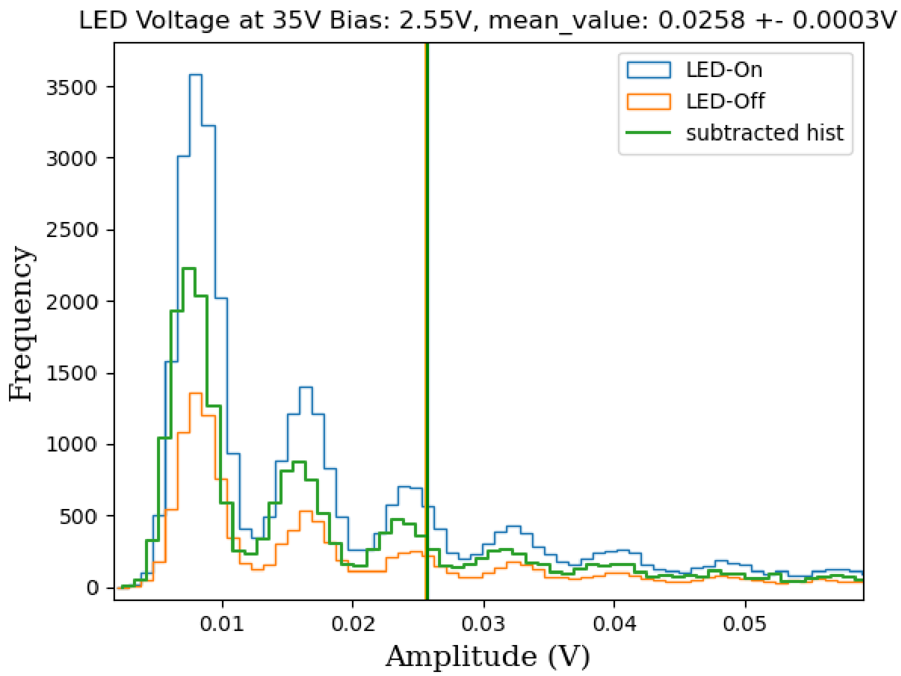


Figure 17: LED subtracted histogram using 405nm LED at 2.55V LED voltage with no filter and double baseline correction (GN).

As expected, at the optimal voltage, the averages are aligned, and SPE statistics are enhanced.

Verifying Extra Scintillation Hypothesis

We inspected the raw waveform data for 405nm LED to verify the assumption that the increase in average amplitude was due to increased scintillation in liquid Xenon from the radioactive decay and cosmic rays.

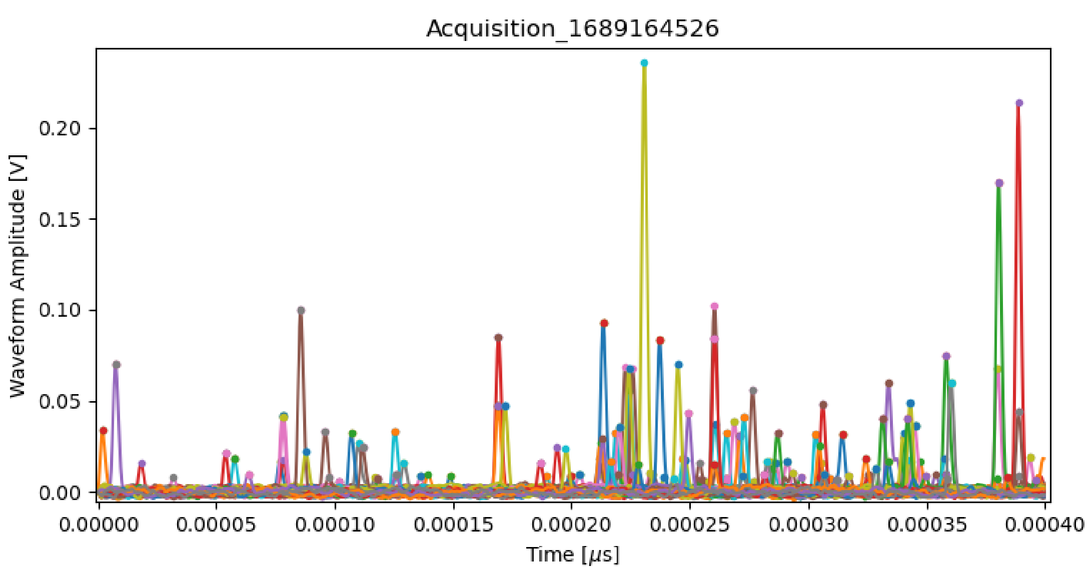


Figure 18: 100 raw waveforms using 405nm LED at 2.55V LED voltage with no filter and double baseline correction (GN).

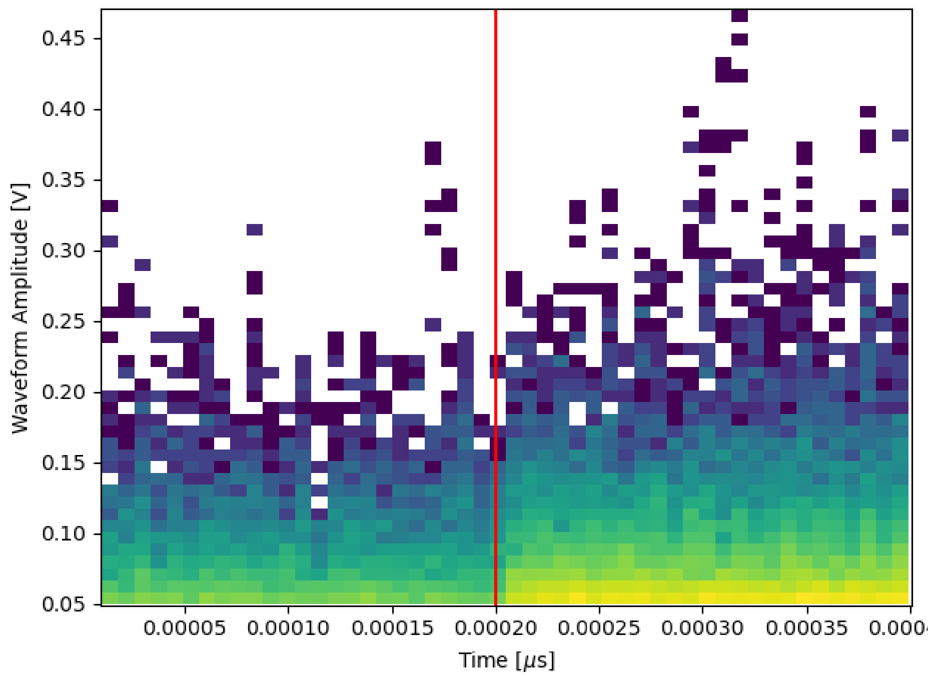


Figure 19: 2D waveform density plot using 405nm LED at 2.55V LED voltage with a no filter and double baseline correction (GN).

Comparing to Figure 3 and Figure 4 (LXe), the frequency of large SPE pulses is a lot lower in Figure 17 and Figure 18 (GN). This is also indicated in the 2D waveform density plots. Inspecting the LED-off window, the LXe waveform amplitude is a lot more filled in the upper regions ($\lesssim$ 0.2V) than in GN.

Quantifying Average Amplitude Variance

To quantify how much the average wave amplitude of LED-on, LED-off, and LED-only vary in LXe w.r.t. to GN, I will use the percentage difference method (P):

$$P = \frac{a-b}{b} \times 100 \text{ (where a > b)}$$

$$\Delta P = P \times \sqrt{\frac{(\Delta a)^2 + (\Delta b)^2}{(a-b)^2} + \frac{(\Delta b)^2}{b^2}}$$

$$P_{\text{LED-on}} \approx 33 \pm 1\%$$

$$P_{\text{LED-off}} \approx 51 \pm 2\%$$

$$P_{\text{LED-only}} \approx 2 \pm 4\%$$

From the percentage difference, it is evident that the subtraction method has the best outcome (1.53% difference), accounting for the skewing of the average wave amplitude in LXe (40.37% for LED-on and 28.38% for LED-off).

VAC

To ensure consistency in methodology, we also implemented the subtraction method in VAC.

Temperature

The LED operating voltage data was collected on August 11th at a temperature similar to the tests in LXe and GN.

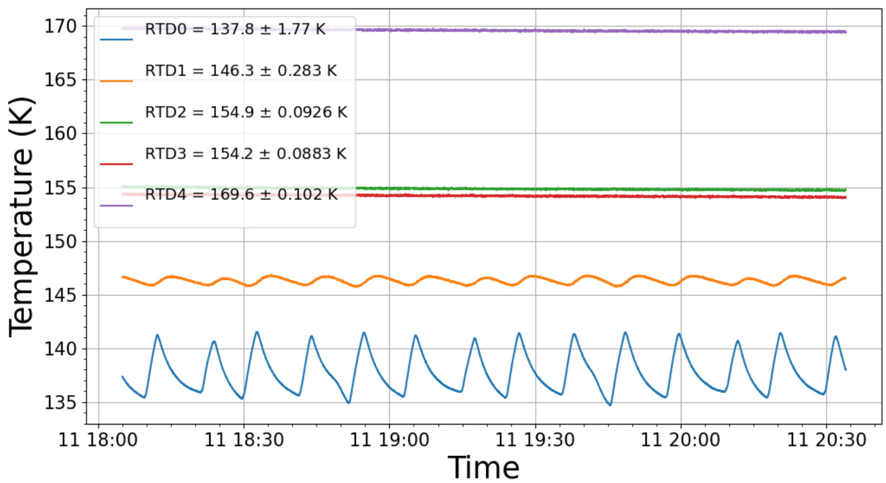


Figure 20: Temperature over the duration of 310nm LED operating voltage data acquisition. The legend shows the average and standard deviation of the temperature during the data collection.

The average temperature at the SiPM during 310nm LED data collection was 169.6 K with a standard deviation of 0.102 $\approx$ 0.1K over the course of 153 minutes. The starting temperature was 169.75K and ended at 169.43K, a total change of .32 K, which is within the uncertainty of the RTD sensors.

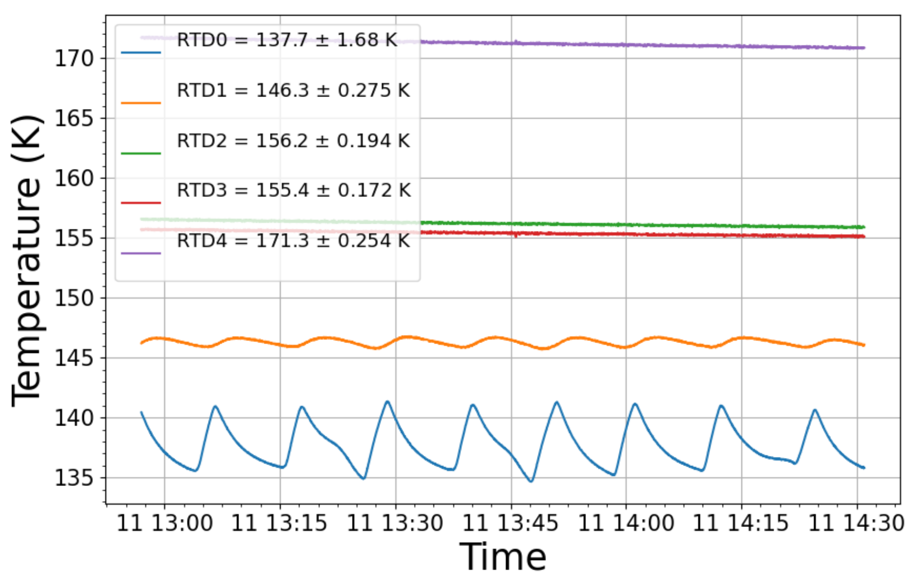


Figure 21: Temperature over the duration of 405nm LED operating voltage data acquisition. The legend shows the average and standard deviation of the temperature during the data collection.

The average temperature at the SiPM during 405nm LED data collection was 171.3 K with a standard deviation of 0.261 $\approx$ 0.3K over the course of 96 minutes. The starting temperature was 171.70K and ended at 170.85K, a total change of .85 K, which is within the uncertainty of the RTD sensors.

Average Amplitude and Ratio Analysis

Using the exact same function generator settings and turned-off filter, we found the average amplitude and ratio at different LED voltages for 310nm and 405nm LED.

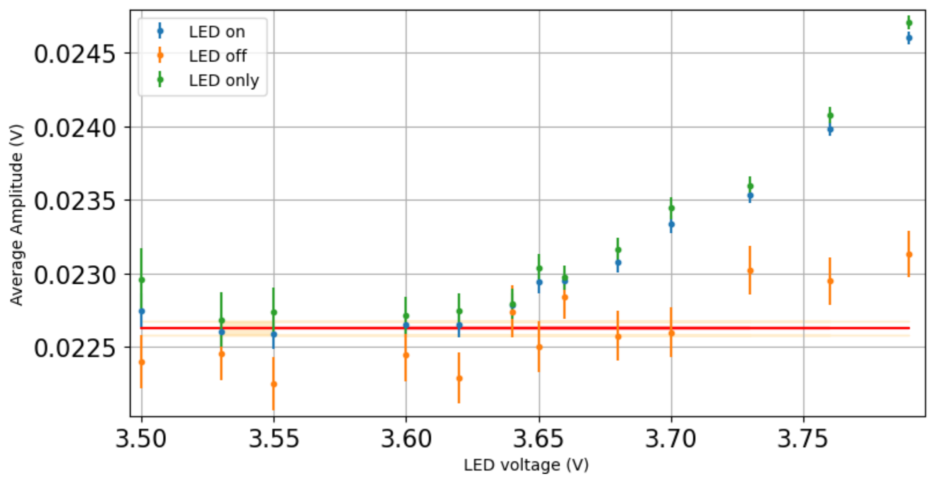


Figure 22: Average waveform amplitude vs LED voltage (310nm) at 35V bias with LED-only (VAC).

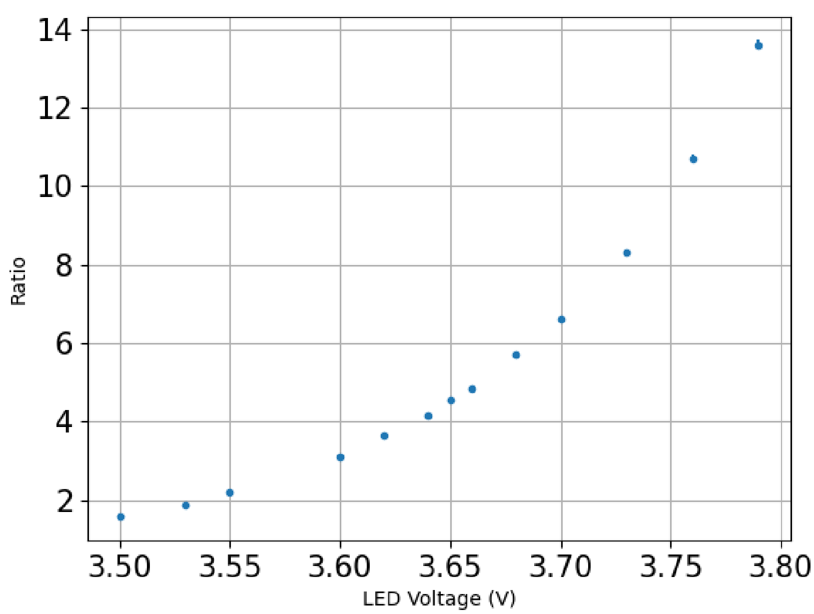


Figure 23: Ratio vs LED voltage (310nm) at 35 bias (VAC).

Inspecting the average amplitude plot (Figure 22) for the 310nm LED, the average amplitude mean for LED-off is 0.02263 ± 0.00005V, which is around 10% lower than in GN. We hypothesize that there is still a small increase in scintillation in GN compared to VAC. Together with the ratio plot (Figure 23), we chose the optimal voltage to be 3.62V.

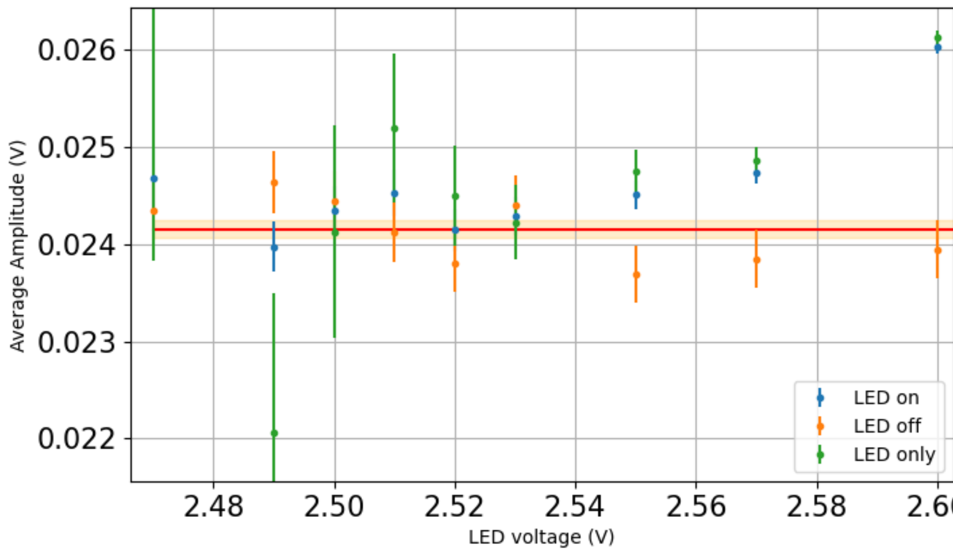


Figure 24: Zoomed average waveform amplitude vs LED voltage (405nm) at 35V bias with LED-only (VAC).

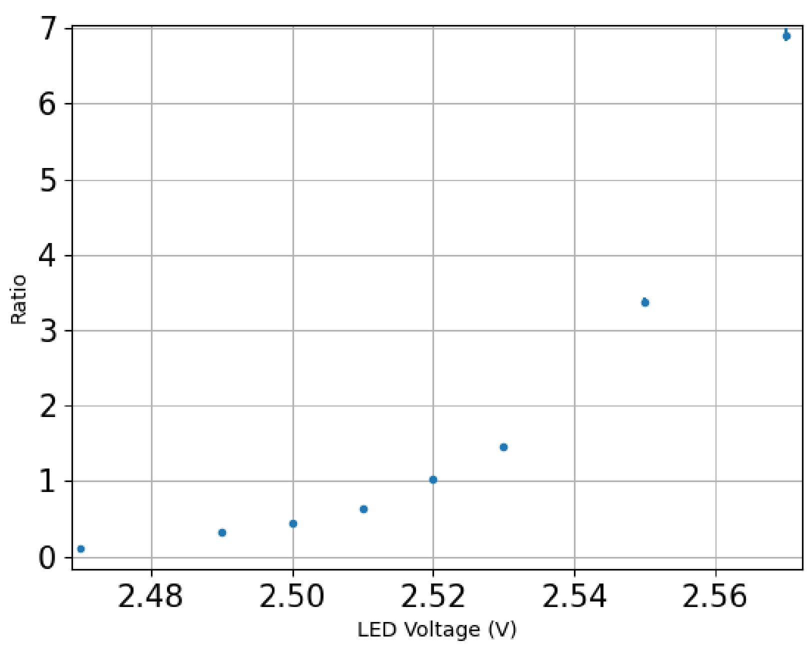


Figure 25: Ratio vs LED voltage (405nm) at 35 bias (VAC).

For 405nm LED in a vacuum, examining the average amplitude plot (Figure 24) and ratio plot (Figure 25), the optimal voltage appears to be 2.53V. Beyond this point, the LED-on average and LED-off average (0.0242 ± 0.0001V) begin to diverge. Prior to this divergence, most of the LED-only points and the average amplitude mean of LED-off overlap within their uncertainties. However, at voltages below $\lesssim$ 2.50V, the ratio approaches 0, rendering the LED-only points inaccurate.

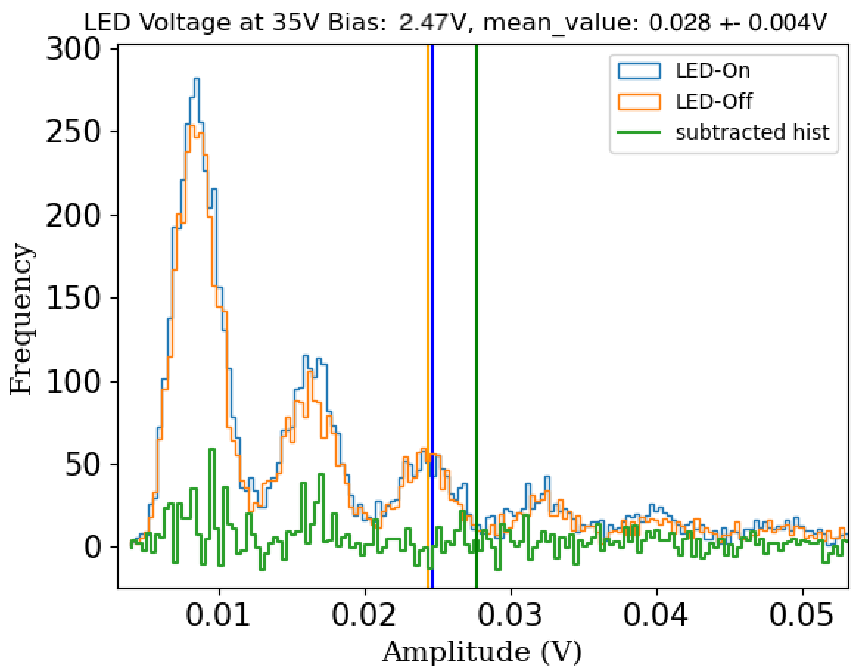


Figure 26: LED subtracted histogram using 405nm LED at 2.47V LED voltage with no filter and double baseline correction (VAC).

Looking at Figure 26, it can be verified that because the ratio is close to 0, the subtracted histogram is not an accurate representation of the wave amplitude distribution.

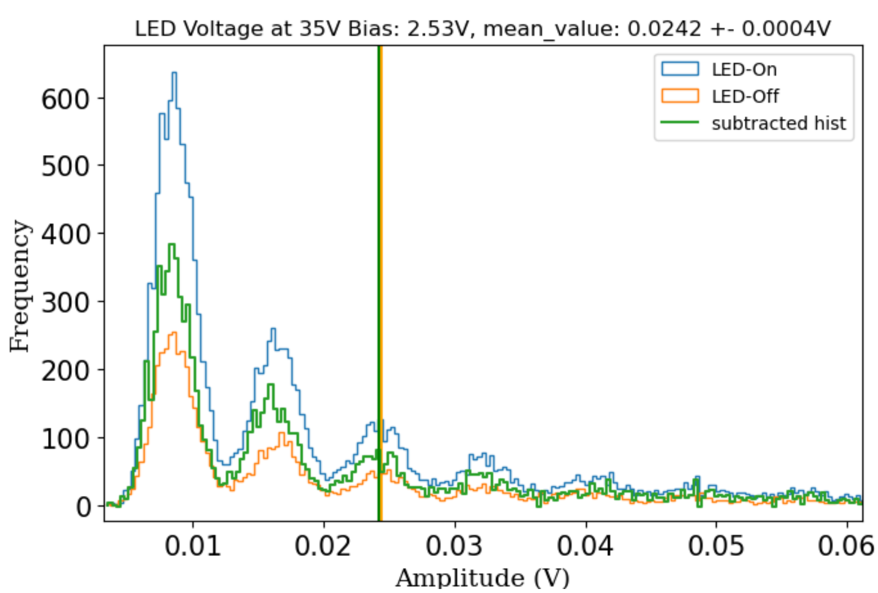


Figure 27: LED subtracted histogram using 405nm LED at 2.53V LED voltage with no filter and double baseline correction (VAC).

At the optimal voltage, the amplitude averages of LED-on, LED-off, and LED-only are aligned with enhanced SPE statistics.

Quantifying Average Amplitude Variance

To quantify how much the average wave amplitude of LED-on, LED-off, and LED-only vary in LXe w.r.t. to VAC and GN w.r.t. VAC, I will again use the percentage difference method (P).

$$P = \frac{a-b}{b} \times 100 \text{ (where a > b)}$$
$$\Delta P = P \times \sqrt{\frac{(\Delta a)^2 + (\Delta b)^2}{(a-b)^2} + \frac{(\Delta b)^2}{b^2}}$$

For LXe w.r.t. VAC:

$$P_{\text{LED-on}} \approx 41 \pm 1\%$$

$$P_{\text{LED-off}} \approx 59 \pm 2\%$$

$$P_{\text{LED-only}} \approx 8 \pm 4\%$$

For GN w.r.t. VAC:

$$P_{\text{LED-on}} \approx 6 \pm 1\%$$

$$P_{\text{LED-off}} \approx 5 \pm 2\%$$

$$P_{\text{LED-only}} \approx 6 \pm 2\%$$

Verifying Extra Scintillation Hypothesis

To confirm the hypothesis that there are fewer large SPE pulses present in VAC compared to GN, we inspected the raw waveforms and 2D waveform density plots at 2.53V.

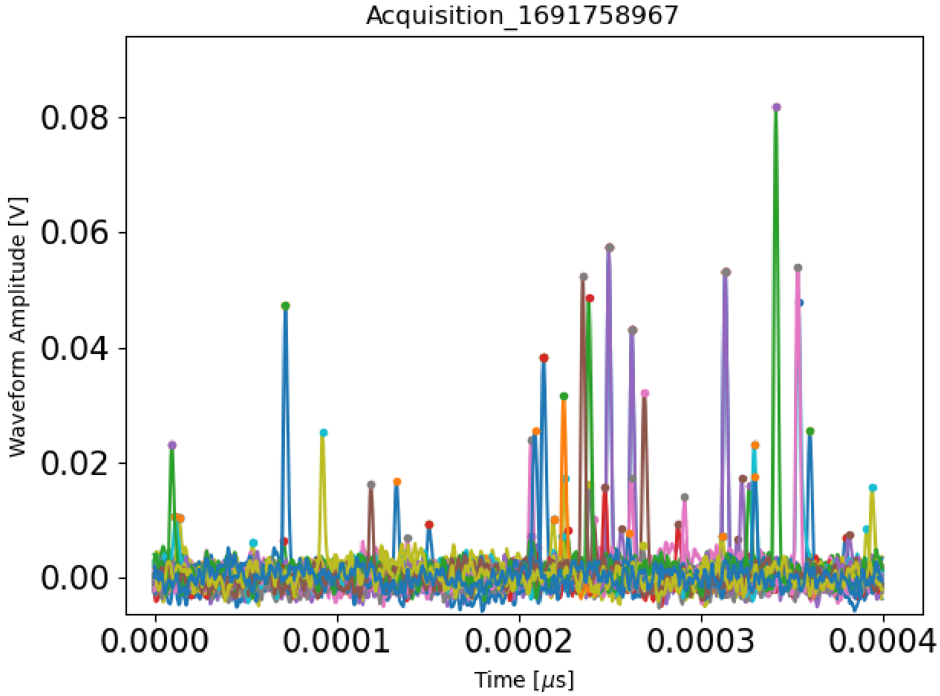


Figure 28: 100 raw waveforms using 405nm LED at 2.53V LED voltage with no filter and double baseline correction (VAC).

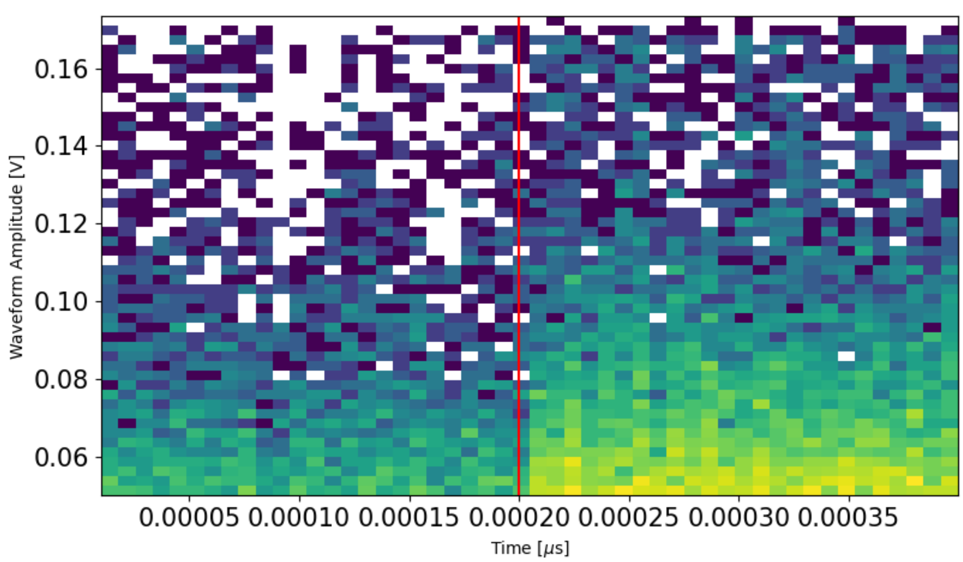


Figure 29: 2D waveform density plot using 405nm LED at 2.53V LED voltage with a no filter and double baseline correction (VAC).

Indeed, when compared to the waveforms in GN (Figure 17 and Figure 18), the VAC 2D density plot does not extend pass 0.1V, leading to a slightly lower average wave amplitude.

Conclusion of the Subtracted Histogram Method

While the subtracted histogram method enables simultaneous acquisition of SPE data along with alpha data in LXe for calculating correlated avalanche events and, consequently, the photon detection efficiency (PDE), it demands a substantial amount of data and time. In the following sections, I will demonstrate the similarity in calculated Correlated Avalanche (CA) across various media and establish that employing GN CA calculation as baseline data is sufficient for PDE computation.

5 Comparison Between Different Media

This section aims to compare the average wave amplitude across three media—LXe, GN, and VAC—by compiling all the data onto the same plots and presenting the values quantitatively in a tabular format. Because the 310nm LED data is not available for the LXe run, I will only compare the 405nm LED data.

Comparison Plots

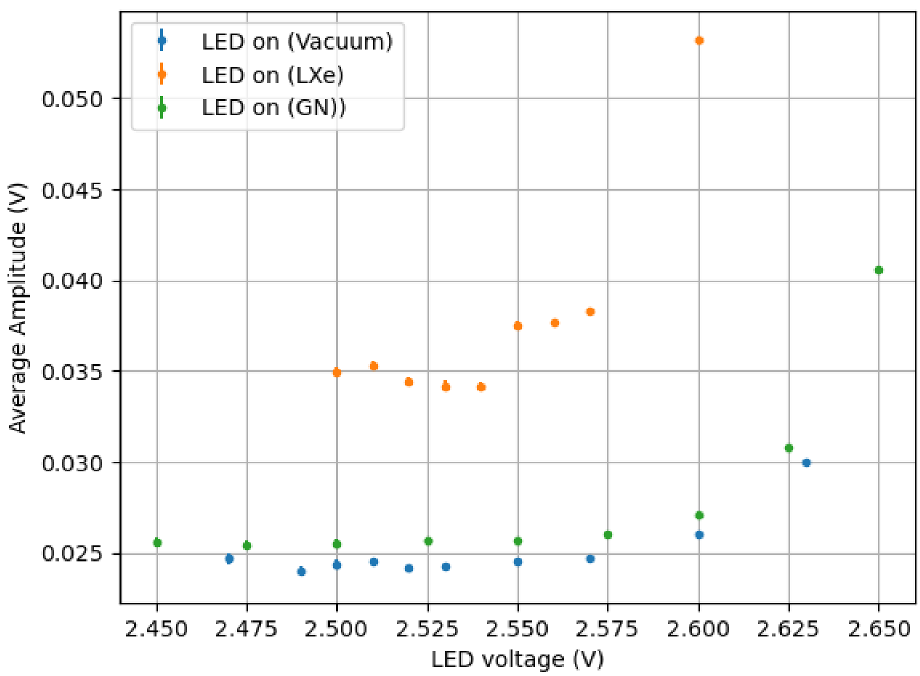


Figure 30: LED-on Average Amplitude vs LED voltage for 405nm LED at 35V bias across LXe, GN, and VAC.

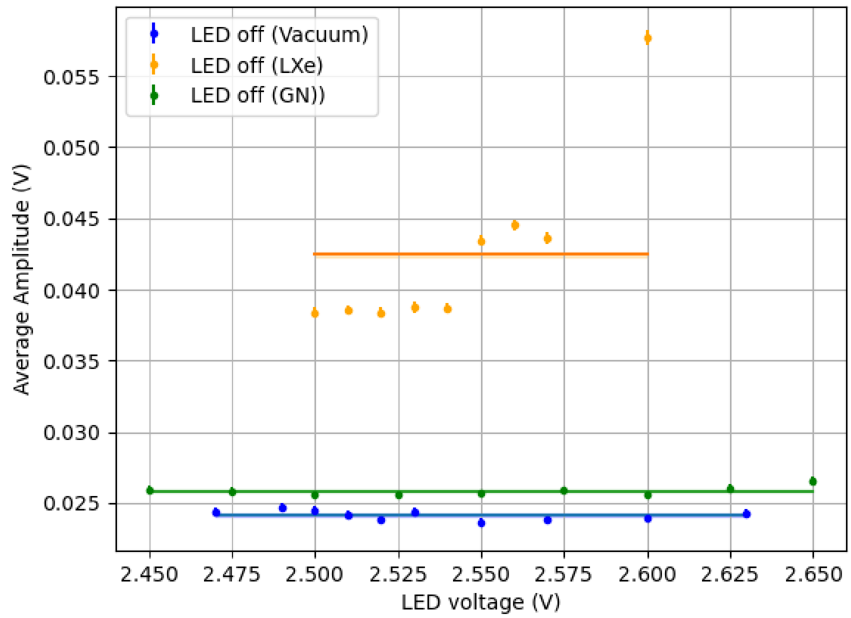


Figure 31: LED-off Average Amplitude vs LED voltage for 405nm LED at 35V bias across LXe, GN, and VAC.

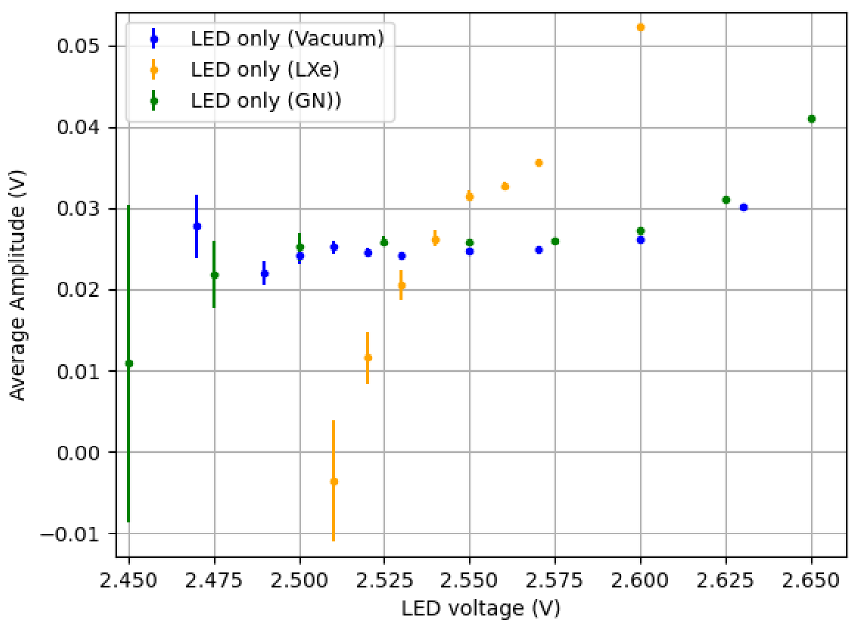


Figure 32: LED-only Average Amplitude vs LED voltage for 405nm LED at 35V bias across LXe, GN, and VAC.

As expected, in both the LED-on and LED-off comparison plot (Figure 30 and Figure 31), the average amplitude values for GN and VAC remain close to each other while the values for LXe are significantly shifted. As mentioned in the LED operating condition section, there is approximately a 40%–45% difference in the LED-on and a 28%–34% difference in the LED-off at the optimal voltage for GN & LXe, and VAC & LXe, respectively. For the LED-only comparison plot (Figure 32), it is evident that the average amplitude of LXe resides with that of both GN and VAC at 2.54V.

Data Points Used

The average amplitude values for the different LED voltage are all taken at 35 bias and shown in the tables below (categorized by medium):

Table 1: Avg. Amplitude of 405nm LED in LXe at 167.9 ± 0.2K

LED voltage (V)	LED-on (V)	LED-off (V)	LED-only (V)
2.51	0.0353 ± 0.0003	0.0386 ± 0.0003	-0.004 ± 0.008
2.52	0.0344 ± 0.0003	0.0384 ± 0.0003	0.012 ± 0.003
2.53	0.0342 ± 0.0003	0.0388 ± 0.0004	0.021 ± 0.002
2.54	0.0342 ± 0.0002	0.0387 ± 0.0004	0.0262 ± 0.0009
2.55	0.0375 ± 0.0002	0.0434 ± 0.0004	0.0314 ± 0.0006
2.56	0.0377 ± 0.0002	0.0445 ± 0.0004	0.0327 ± 0.0005
2.57	0.0383 ± 0.0002	0.0436 ± 0.0004	0.0355 ± 0.0003
2.60	0.0532 ± 0.0002	0.0577 ± 0.0005	0.0523 ± 0.0002

Table 2: Avg. Amplitude of 405nm LED in GN at 171.37 ± 0.01K

LED voltage (V)	LED-on (V)	LED-off (V)	LED-only (V)
2.450	0.0256 ± 0.0003	0.0260 ± 0.0003	0.0108 ± 0.0195
2.475	0.0254 ± 0.0002	0.0258 ± 0.0003	0.0218 ± 0.0042
2.500	0.0255 ± 0.0002	0.0256 ± 0.0003	0.0252 ± 0.0018
2.525	0.0257 ± 0.0002	0.0256 ± 0.0003	0.0259 ± 0.0006
2.550	0.0257 ± 0.0002	0.0257 ± 0.0003	0.0258 ± 0.0003
2.575	0.0260 ± 0.0001	0.0259 ± 0.0003	0.0260 ± 0.0002
2.600	$0.027\,13 \pm 0.000\,08$	0.0256 ± 0.0003	0.0273 ± 0.0001
2.625	$0.030\,80 \pm 0.000\,06$	0.0261 ± 0.0003	0.0310 ± 0.0001
2.650	$0.040\,61 \pm 0.000\,05$	0.0266 ± 0.0003	0.0409 ± 0.0001

Table 3: Avg. Amplitude of 405nm LED in VAC at 171.3 ± 0.3K

LED voltage (V)	LED-on (V)	LED-off (V)	LED-only (V)
2.47	0.0247 ± 0.0003	0.0244 ± 0.0003	0.028 ± 0.003
2.49	0.0240 ± 0.0003	0.0246 ± 0.0003	0.022 ± 0.001
2.50	0.0244 ± 0.0003	0.0245 ± 0.0003	0.024 ± 0.001
2.51	0.0245 ± 0.0004	0.0241 ± 0.0003	0.0252 ± 0.0008
2.52	0.0241 ± 0.0002	0.0238 ± 0.0003	0.0245 ± 0.0005
2.53	0.0243 ± 0.0002	0.0244 ± 0.0003	0.0242 ± 0.0004
2.55	0.0245 ± 0.0002	0.0237 ± 0.0003	0.0248 ± 0.0002
2.57	0.0247 ± 0.0001	0.0239 ± 0.0003	0.0249 ± 0.0001
2.60	$0.026\,02 \pm 0.000\,07$	0.0240 ± 0.0003	$0.026\,13 \pm 0.000\,07$
2.63	$0.029\,99 \pm 0.000\,05$	0.0243 ± 0.0003	$0.030\,10 \pm 0.000\,04$

Optimal LED Voltage

The optimal LED voltages for each media is presented in the Table 4, where the average amplitude for each LED status is shown. In addition, I also included the percentage difference of average amplitude for LED-only with respect to VAC.

Table 4: Optimal voltage and absolute difference w.r.t VAC

	Opt. LED V	LED-off (mean±err)	LED-on (mean±err)	LED-only (mean±err)	ΔLED-only
LXe	2.54V	0.0375 ± 0.0002V	0.0387 ± 0.0004V	0.0262 ± 0.0009V	0.0020 ± 0.0010V
GN	2.55V	0.0257 ± 0.0002V	0.0257 ± 0.0003V	0.0258 ± 0.0003V	0.0016 ± 0.0005V
VAC	2.53V	0.0243 ± 0.0002V	0.0244 ± 0.0003V	0.0242 ± 0.0004V	0V

In the ΔLED-only section, it's noted that the LED-only average amplitudes exhibit overlapping absolute differences and errors with respect to VAC. This implies that employing the average amplitude for LED-only across different media should yield CA data that is analogous to one another.

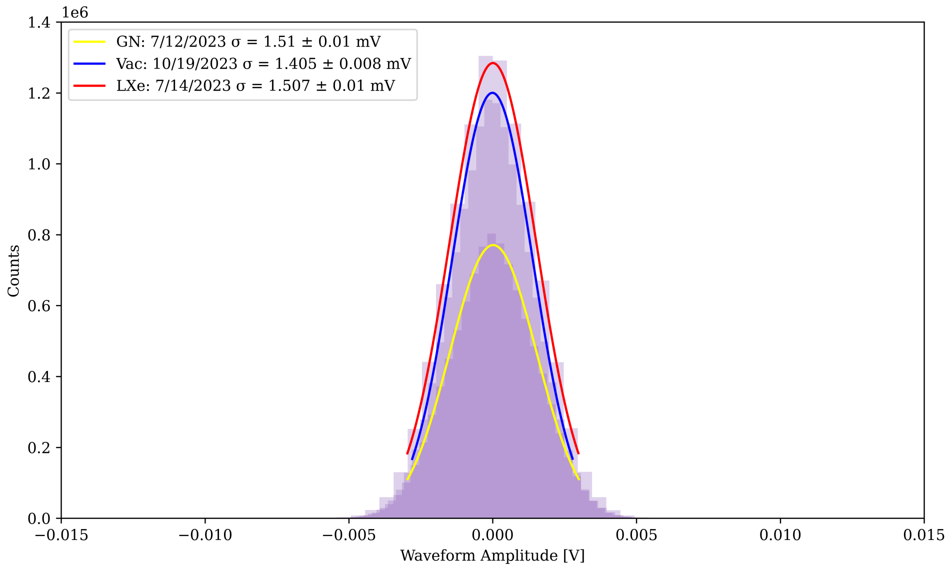


Figure 33: Baseline distribution overlay for GN, LXe, and VAC (Oct.19th) runs with standard deviation.

Looking at the baseline Gaussian distribution of GN, LXe, and VAC (used a baseline data from another VAC run as we did not have one for the August run), the ΔLED-only values are within the range of baseline mean and so the difference is ideally close to 0 or what should be the baseline.

6 LED CA Calculation

This section fulfills a dual role: (1) it outlines our methodology for processing SPE data to compute the CA necessary for PDE calculation, and (2) it performs a comparative analysis of CA across LXe, GN, and VAC, employing the histogram subtraction method. Furthermore, it demonstrates that utilizing LED-only average amplitudes for CA calculation yields analogous results.

For all SPE analysis, a 400kHz low pass filter is used to filter out background noise at lower biases.

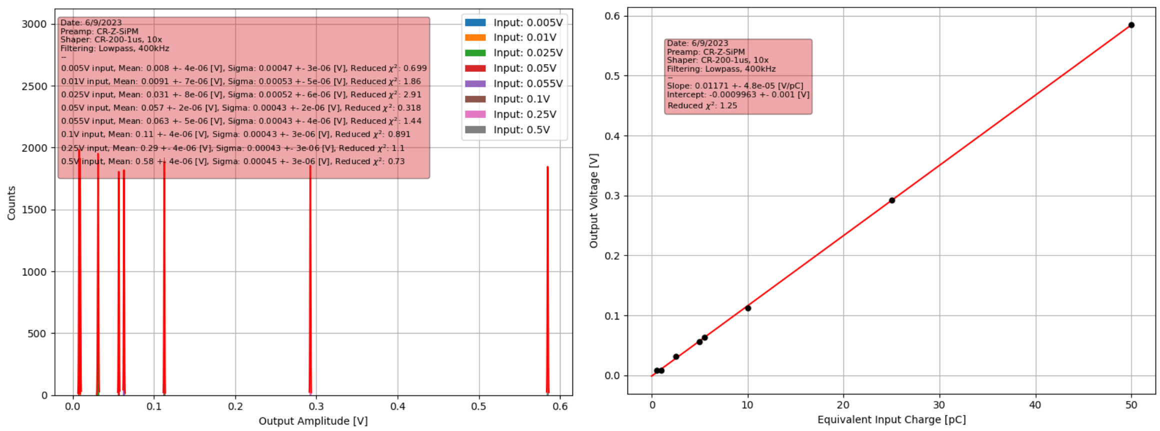


Figure 34: 1 μs shaper with gain 1 activated and gain 2 deactivated (with filter), featuring a gain calibration factor of $0.01171 \pm 5 \times 10^{-5}$ V/pC.

LXe

As indicated in the temperature conditions section, the mean temperature at which the data was collected approximates to 168.360 ± 0.003K.

LED Comparison

The purpose of the LED comparison graphs is to illustrate the effect of LED on the number of detected peaks. Inspecting the peak locations will also help determine the boundaries to Gauss fit. We used an LED voltage of 2.54V, as indicated in the LED operating condition section.

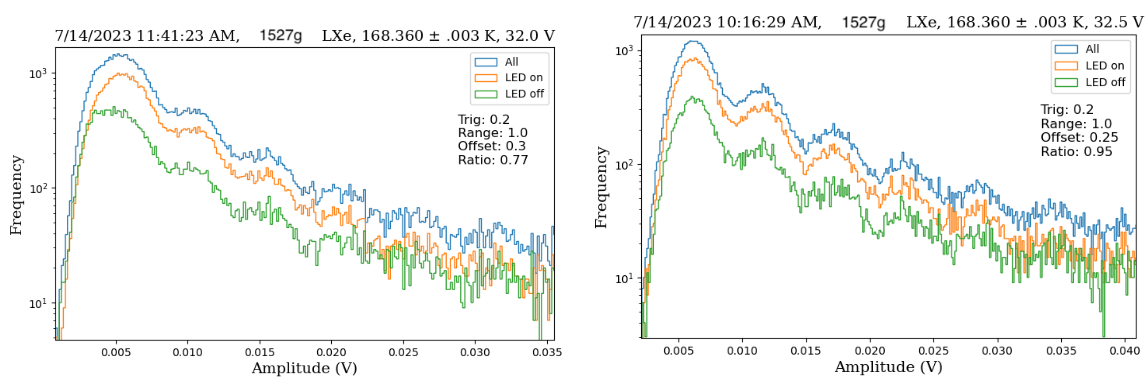


Figure 35: Two LED on/off comparison graphs (32.0-32.5V).

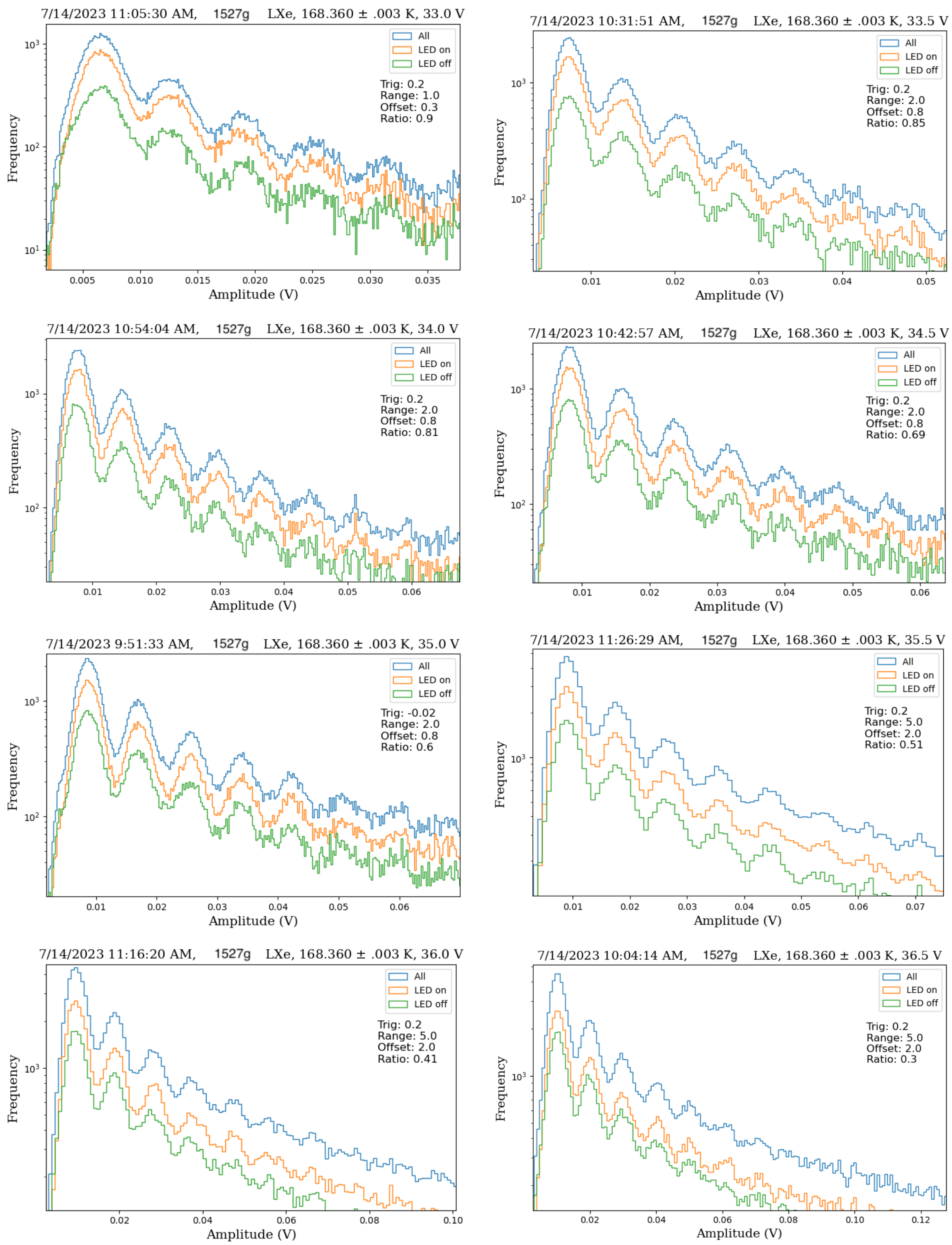


Figure 36: Eight LED on/off comparison graphs (33.0-36.5V).

Multi-Gaussian Fits

A model function consisting of nine Gaussians plus a line is used to fit the histogram and determine the location of each peak in the finger plot. The error on the peak location is taken to be the standard error computed by the fit. The histogram at 32V could not be Gaussian fitted.

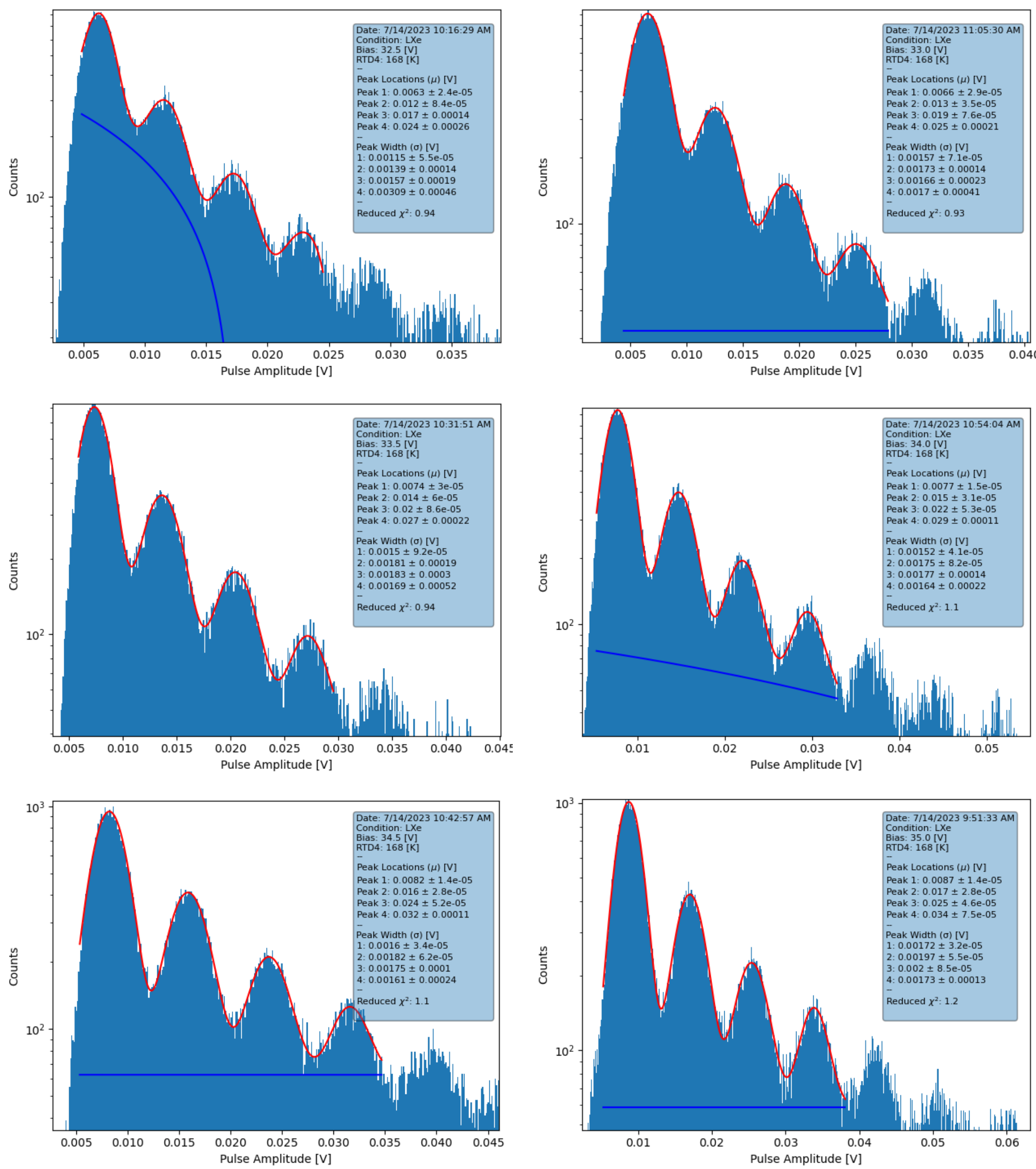


Figure 37: Six Gaussian model functions (red) plus a linear offset (blue) at each bias voltage (32.5-35V).

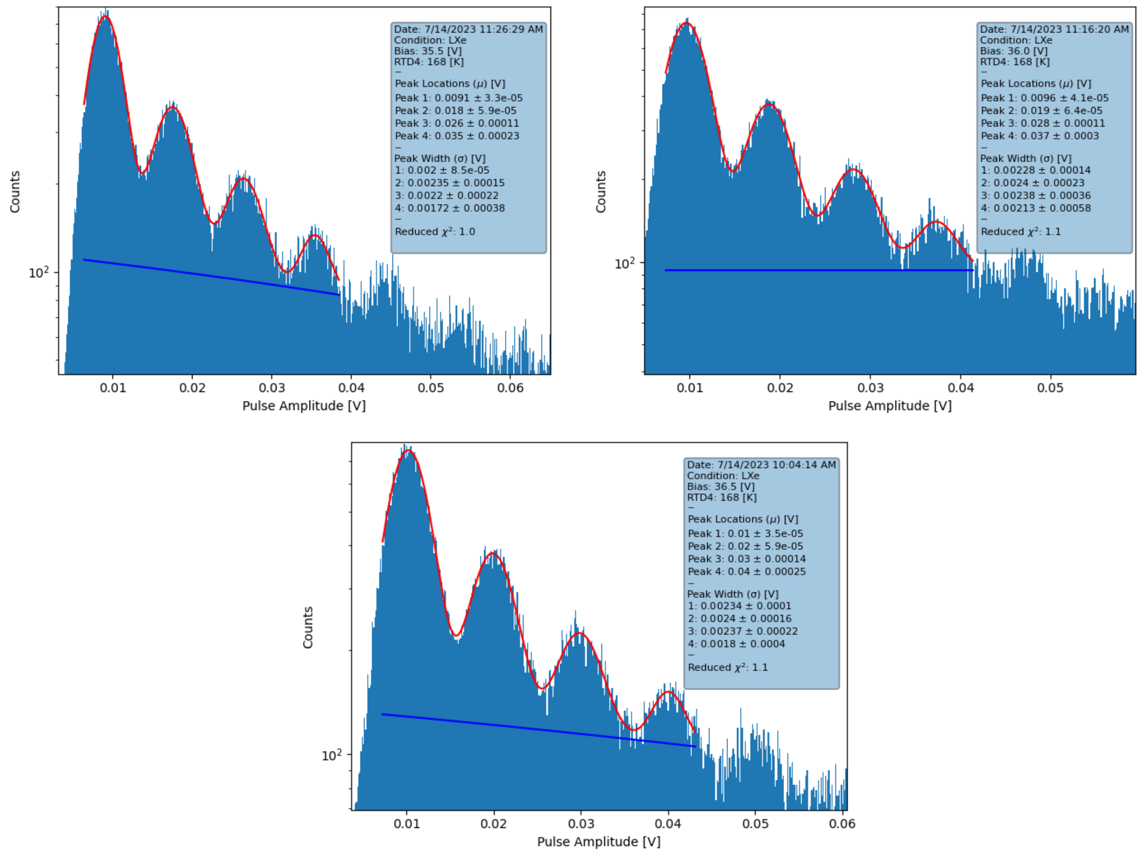


Figure 38: Three Gaussian model functions (red) plus a linear offset (blue) at each bias voltage (35.5-36.5V).

Linear Fits (Average SPE Amplitude)

The SPE amplitude is extracted from the plots in Figure 37 and Figure 38 by computing the difference in amplitude between each of the fingers. Since each finger corresponds to a quantized number of photoelectrons, the average difference in amplitude between neighboring fingers is a robust estimate of the SPE amplitude. The amplitude is characterized by the slope of a linear fit of the peak amplitude versus the peak number. Calculating the slope at each bias voltage, we see that the amplitude of a pulse resulting from a single microcell activation increases linearly with bias voltage. We can interpolate this line down to the x-intercept, where (in theory) there is no activity in the device. This value is the breakdown voltage.

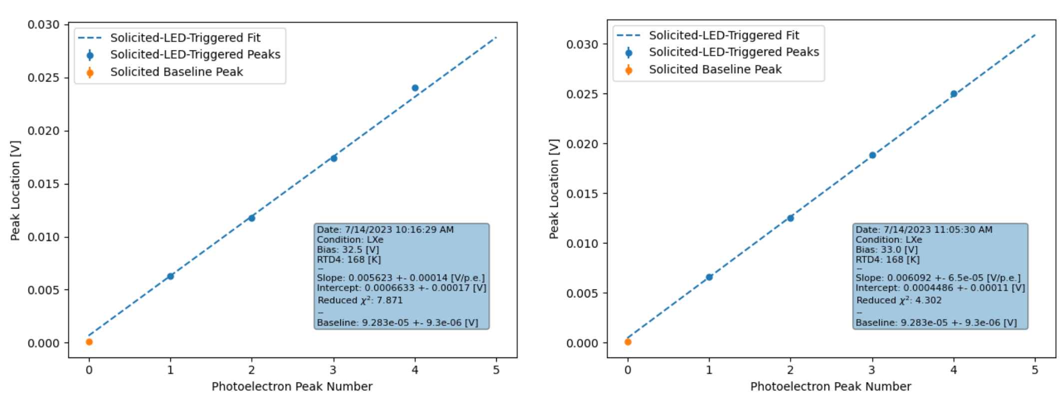


Figure 39: Two linear fits to determine average SPE amplitude at each bias voltage (32.5-33V).

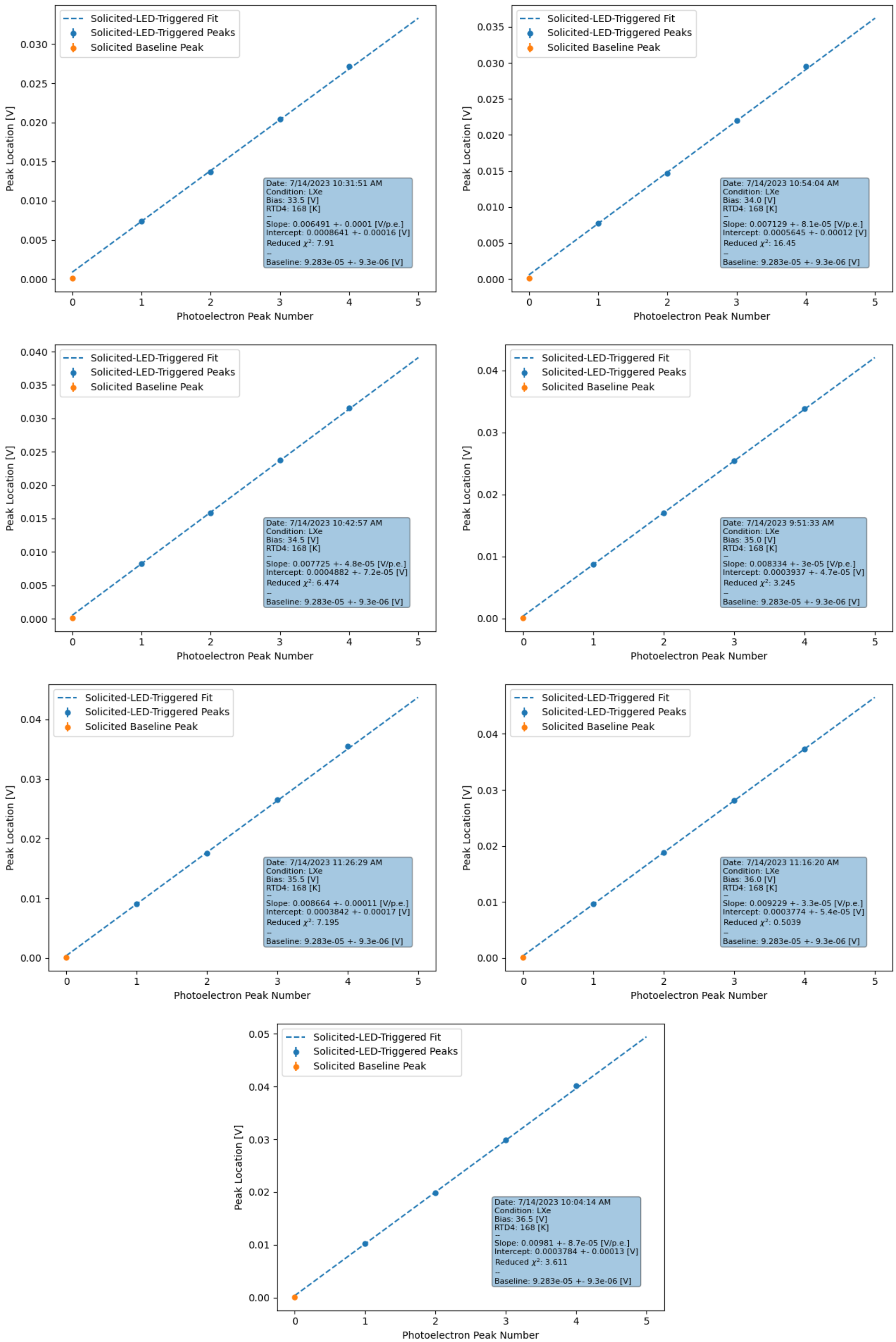


Figure 40: Seven linear fits to determine average SPE amplitude at each bias voltage (33.5-36.5V).

Breakdown Voltage Calculation

The breakdown voltage is defined as the voltage after which the SiPM operates in Geiger-mode. Determination of this value allows us to calculate the overvoltage as $V_{ov} = V_{bias} - V_{breakdown}$. To pinpoint the voltage at which the SPE amplitude is zero—the breakdown voltage—we fit a line through the data we have collected and identify the x-intercept. The breakdown voltage was measured to be 27.1 ± 0.2 V.

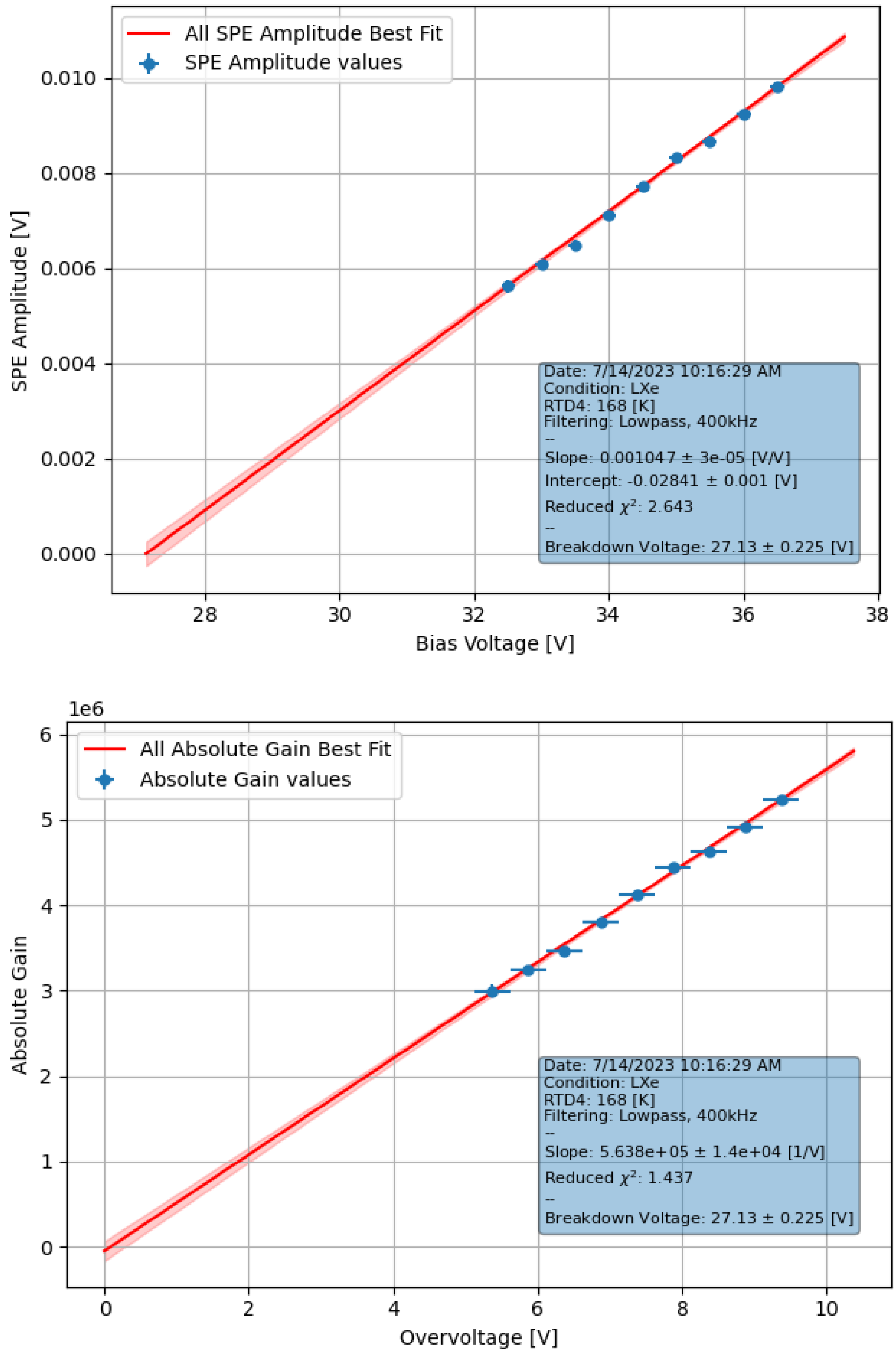


Figure 41: Linear fit to the breakdown voltage. Top: Measured SPE amplitude vs bias. Bottom: Absolute amplitude vs overvoltage.

Correlated Avalanches

For our purposes, we define the average number of correlated avalanches per activated microcell to be:

$$\langle\Lambda\rangle = \frac{1}{N}\sum_{i=1}^{N}\frac{A_i}{\bar{A}_{SPE}} - 1$$

Where A_i is the amplitude of a pulse i and $\bar{A}_{SPE}$ is the average amplitude of a pulse resulting from the activation of a single microcell ("single photon event"). As discovered in the operating voltage section, the additional scintillation caused by radioactive decay and cosmic rays in liquid Xenon skews A_i. This necessitates the use of the average wave amplitude obtained from the LED-only histograms using the histogram subtraction method.

$\langle\Lambda\rangle$ for all overvoltages is found by fitting an empirical analytic function to the data:

$$\langle\Lambda\rangle = \frac{A\exp\left(B * V_{OV}\right) + 1}{A+1} - 1,$$

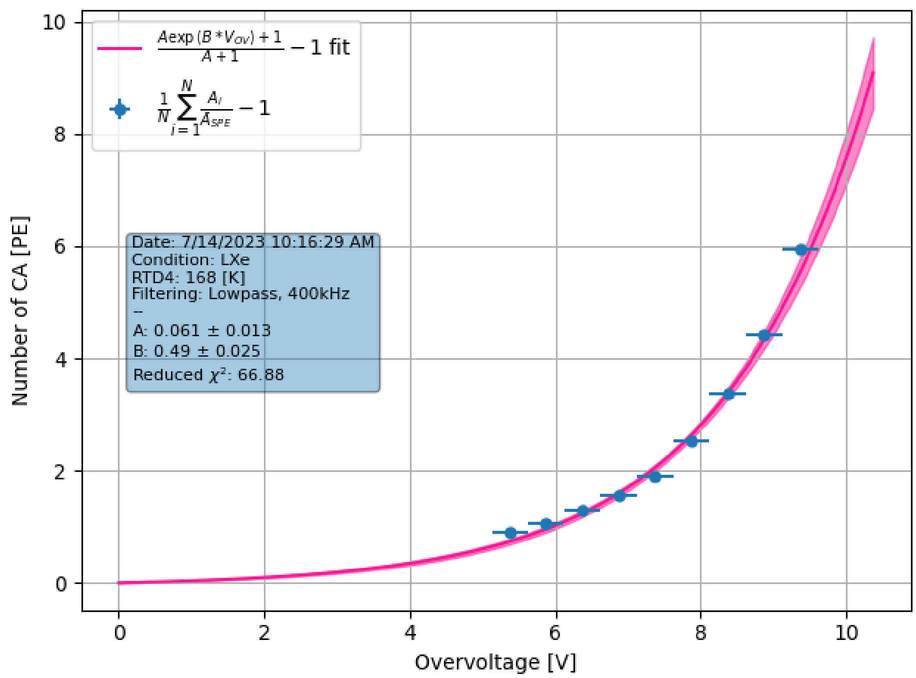


Figure 42: Correlated avalanche probability as a function of overvoltage. Horizontal error bars on the CA probability represent the error on the breakdown voltage as determined by the linear fit in Figure 41. Data taken at 168.360 ± 0.003K in LXe in July of 2023

GN

As indicated in the temperature conditions section, the mean temperature at which the data was collected approximates to 171K.

LED Comparison

Using the same method as LXe, we tested the effect of LED on the number of detected peaks in GN. We used an LED voltage of 2.55V, as indicated in the LED operating condition section.

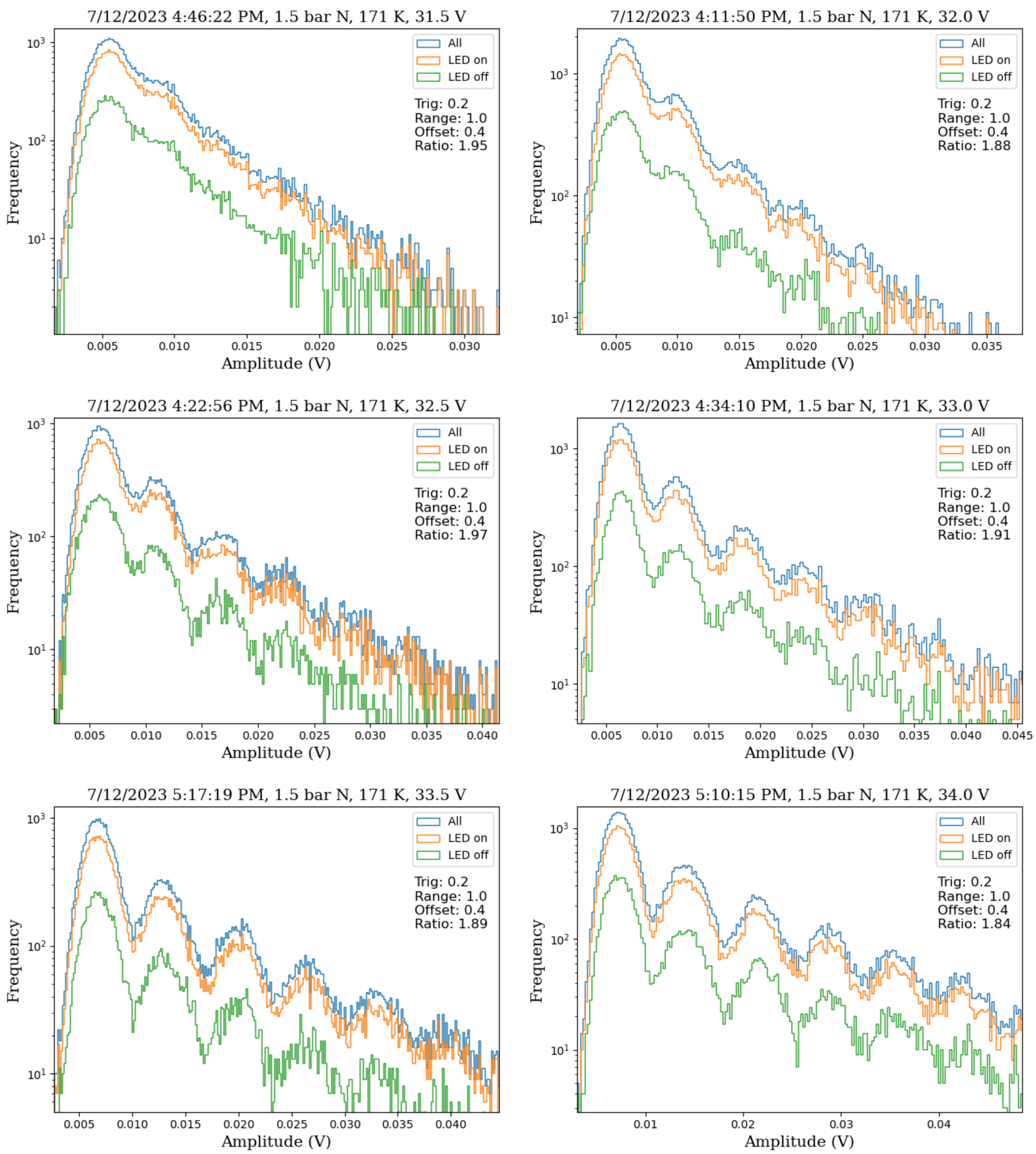


Figure 43: Six LED on/off comparison graphs (31.5-34V).

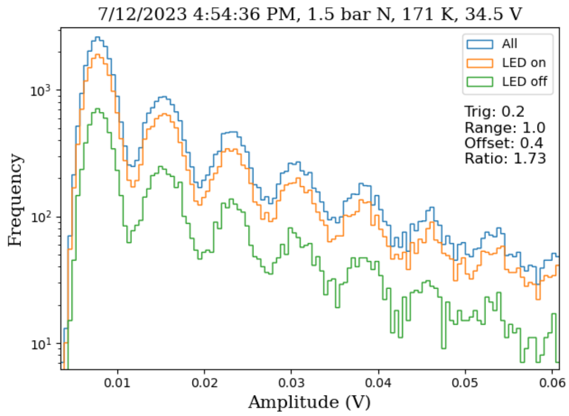


Figure 44: Two LED on/off comparison graphs (34.5-35V).

Multi-Gaussian Fits

A model function consisting of six Gaussians plus a line is used to fit the histogram and determine the location of each peak in the finger plot. The error on the peak location is taken to be the standard error computed by the fit. The histogram at 31.5V and 32V could not be Gaussian fitted. For enhanced accuracy, I fitted the histograms with 5 peaks for biases from 34V-35V.

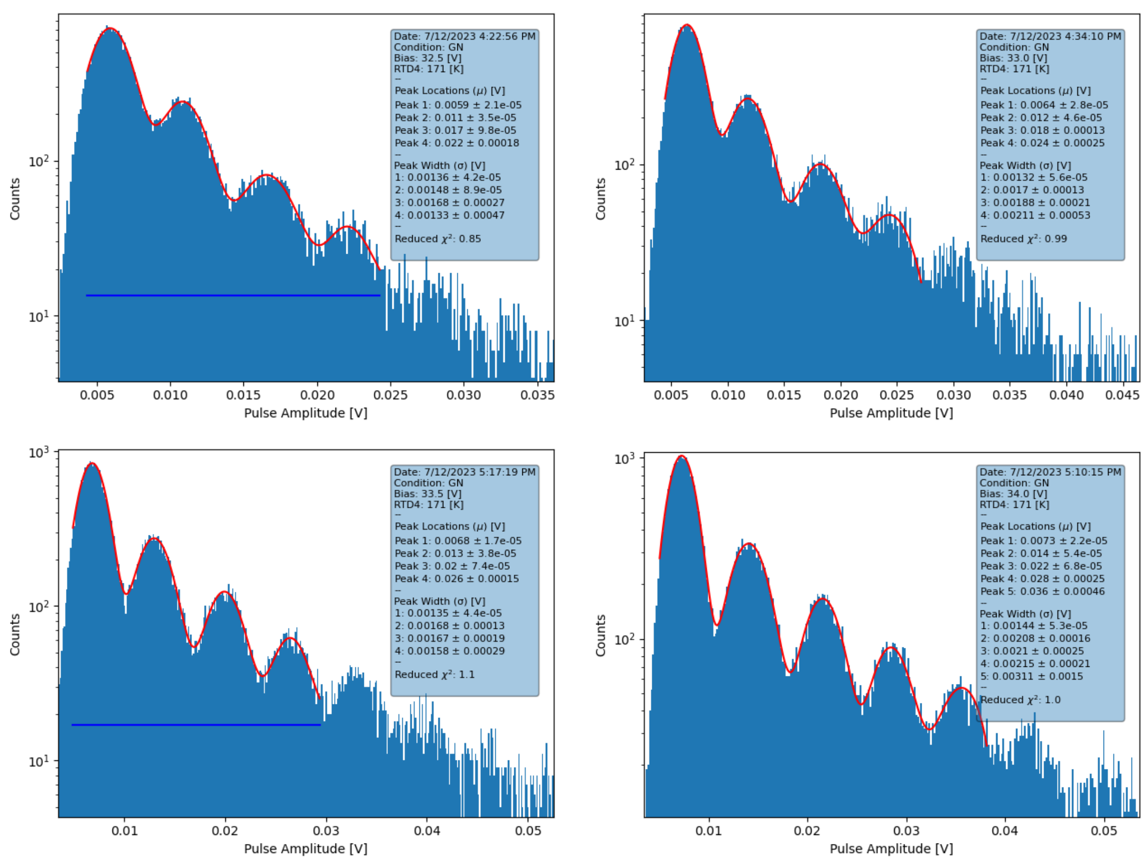


Figure 45: Four Gaussian model functions (red) plus a linear offset (blue) at each bias voltage (32.5-34V).

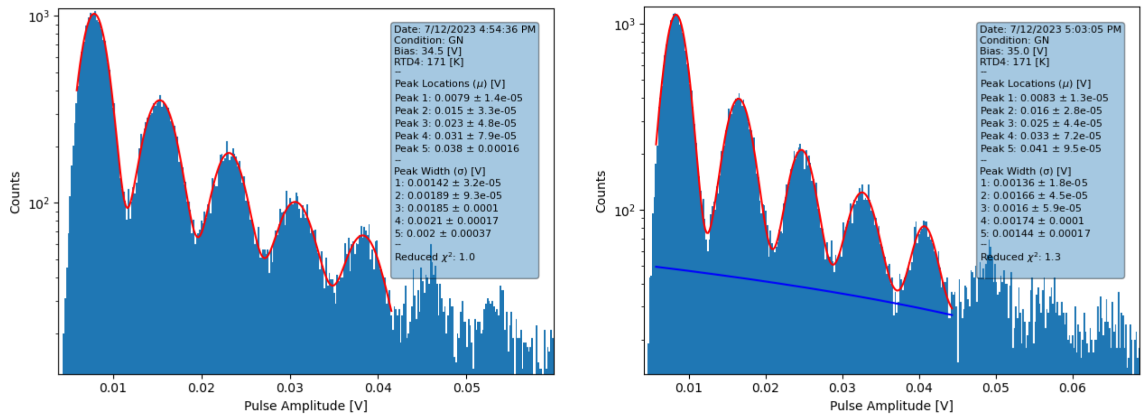


Figure 46: Two Gaussian model functions (red) plus a linear offset (blue) at each bias voltage (34.5-35V).

Linear Fits (Average SPE Amplitude)

Using the same method as in LXe, the SPE amplitude is extracted from the plots in Figure 45 and Figure 46 by computing the difference in amplitude between each of the fingers.

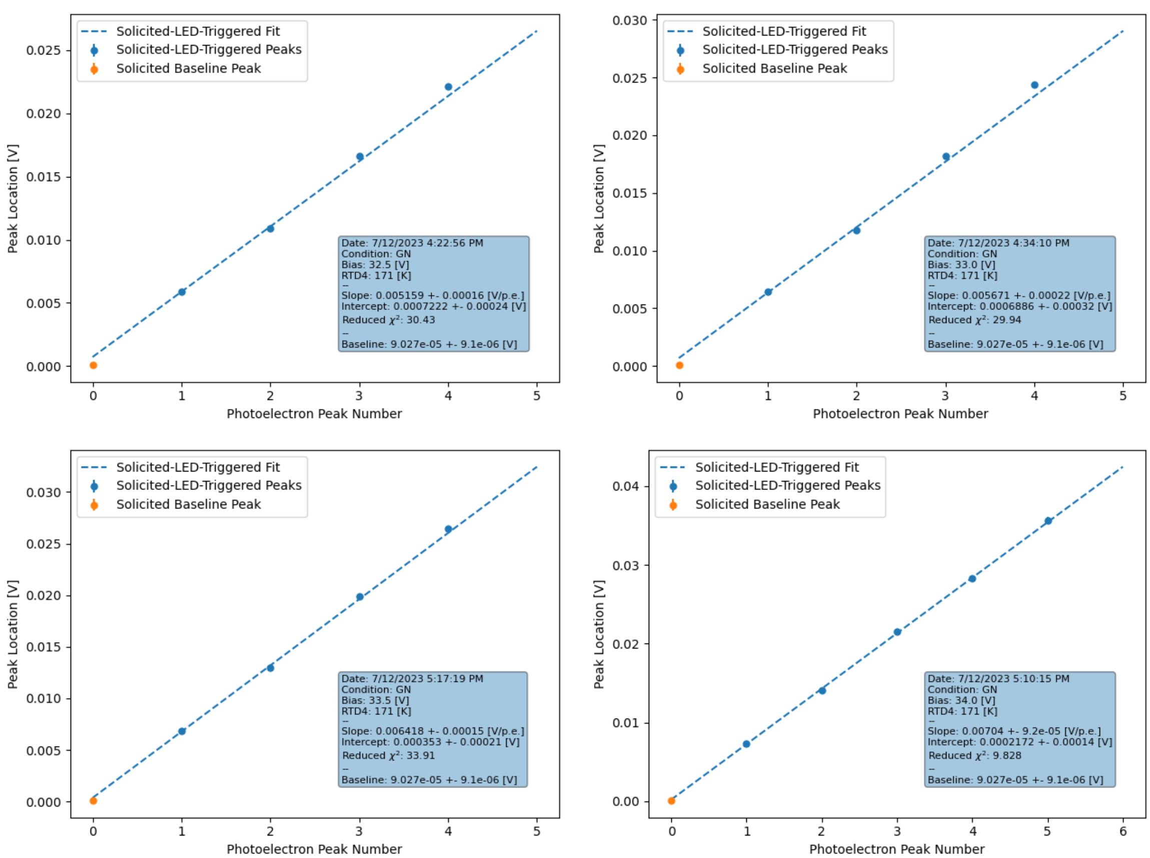


Figure 47: Four linear fits to determine average SPE amplitude at each bias voltage (32.5-34V).

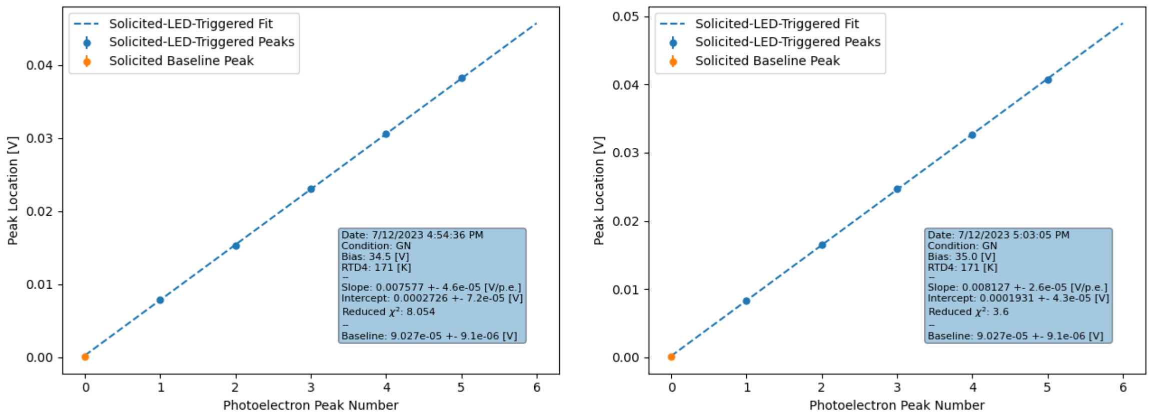
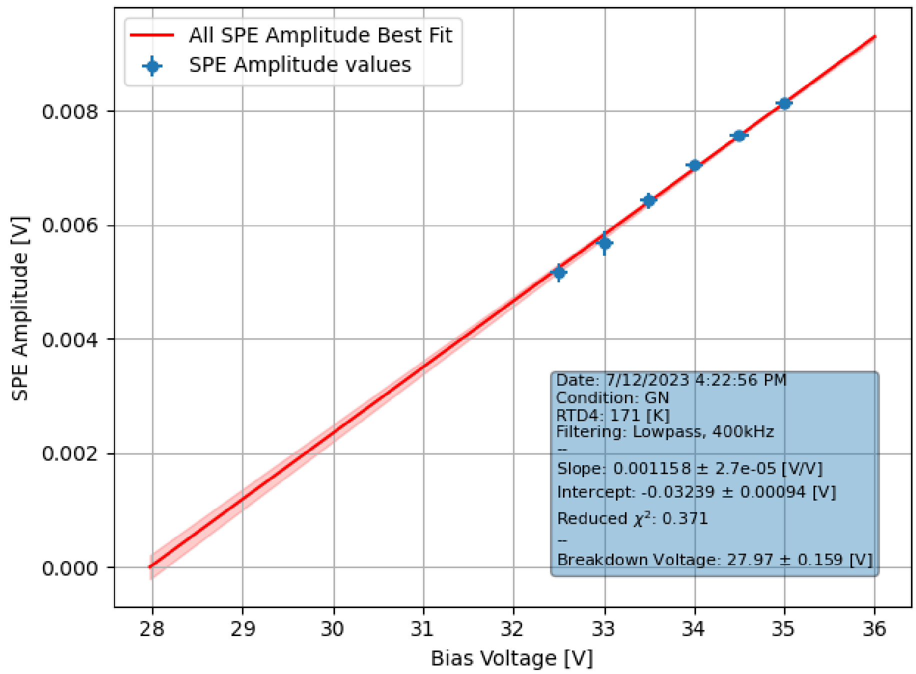


Figure 48: Two linear fits to determine average SPE amplitude at each bias voltage (34.5-35V).

Breakdown Voltage Calculation

The breakdown voltage is defined as the voltage after which the SiPM operates in Geiger-mode. Using the same method as in LXe, we fit a line through the data we have collected to identify the x-intercept and thus, the breakdown voltage. The breakdown voltage was measured to be 28.0 ± 0.2 V.



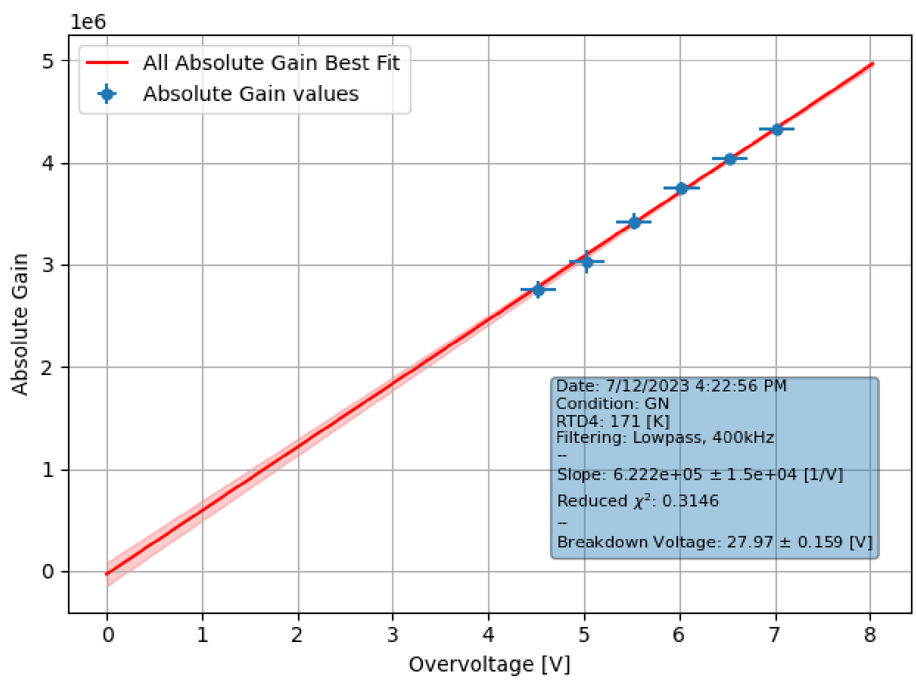


Figure 49: Linear fit to the breakdown voltage. Top: Measured SPE amplitude vs bias. Bottom: Absolute amplitude vs overvoltage.

Correlated Avalanches

Using the same method as LXe, we define the average number of correlated avalanches per activated microcell to be:

$$\langle \Lambda \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{A_i}{\bar{A}_{SPE}} - 1$$

Where A_i is the amplitude of a pulse i and $\bar{A}_{SPE}$ is the average amplitude of a pulse resulting from the activation of a single microcell ("single photon event"). As revealed in the operating voltage section, the average wave amplitudes for LED-on, LED-off, and LED-only fall within each other's uncertainty ranges. For consistency with the LXe CA, I also used the average amplitude acquired from the LED-only histogram.

$\langle \Lambda \rangle$ for all overvoltages is found by fitting an empirical analytic function to the data:

$$\langle \Lambda \rangle = \frac{A \exp{(B * V_{OV})} + 1}{A + 1} - 1,$$

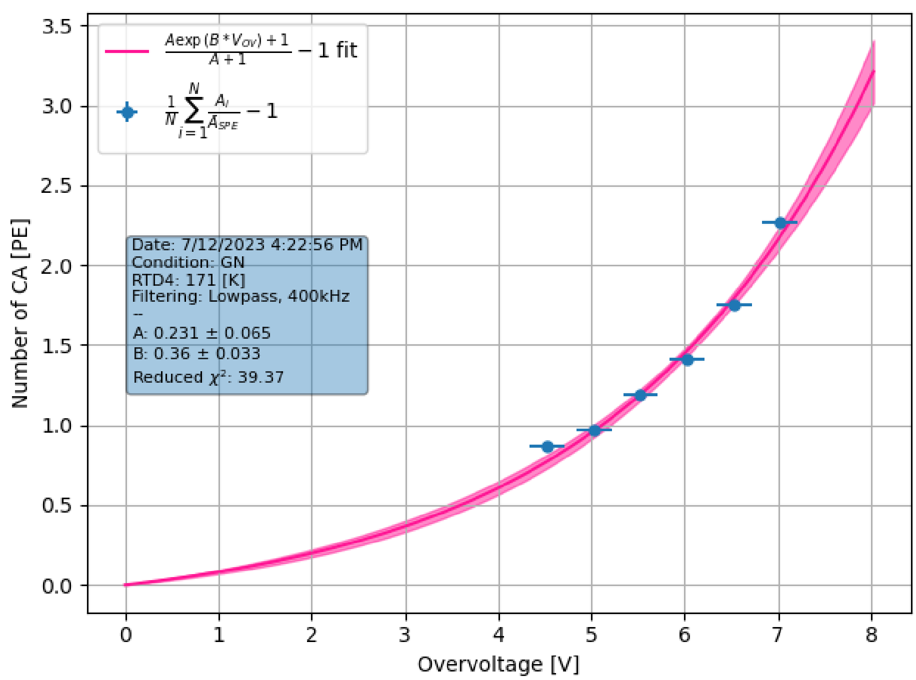


Figure 50: Correlated avalanche probability as a function of overvoltage. Horizontal error bars on the CA probability represent the error on the breakdown voltage as determined by the linear fit in Figure 49. Data taken at 171 K in GN in July of 2023

VAC

As indicated in the temperature conditions section, the mean temperature at which the data was collected approximates to 170.2 $\pm$ 0.3K.

LED Comparison

Using the same method as LXe, we tested the effect of LED on the number of detected peaks in VAC. We used an LED voltage of 2.53V, as indicated in the LED operating conditions section. Upon inspecting the histograms, we observed that at higher overvoltage (look at 36.5V), there appears to be additional scintillation activity due to LXe residuals, resulting in a minor spike in the frequency of high-amplitude waves.

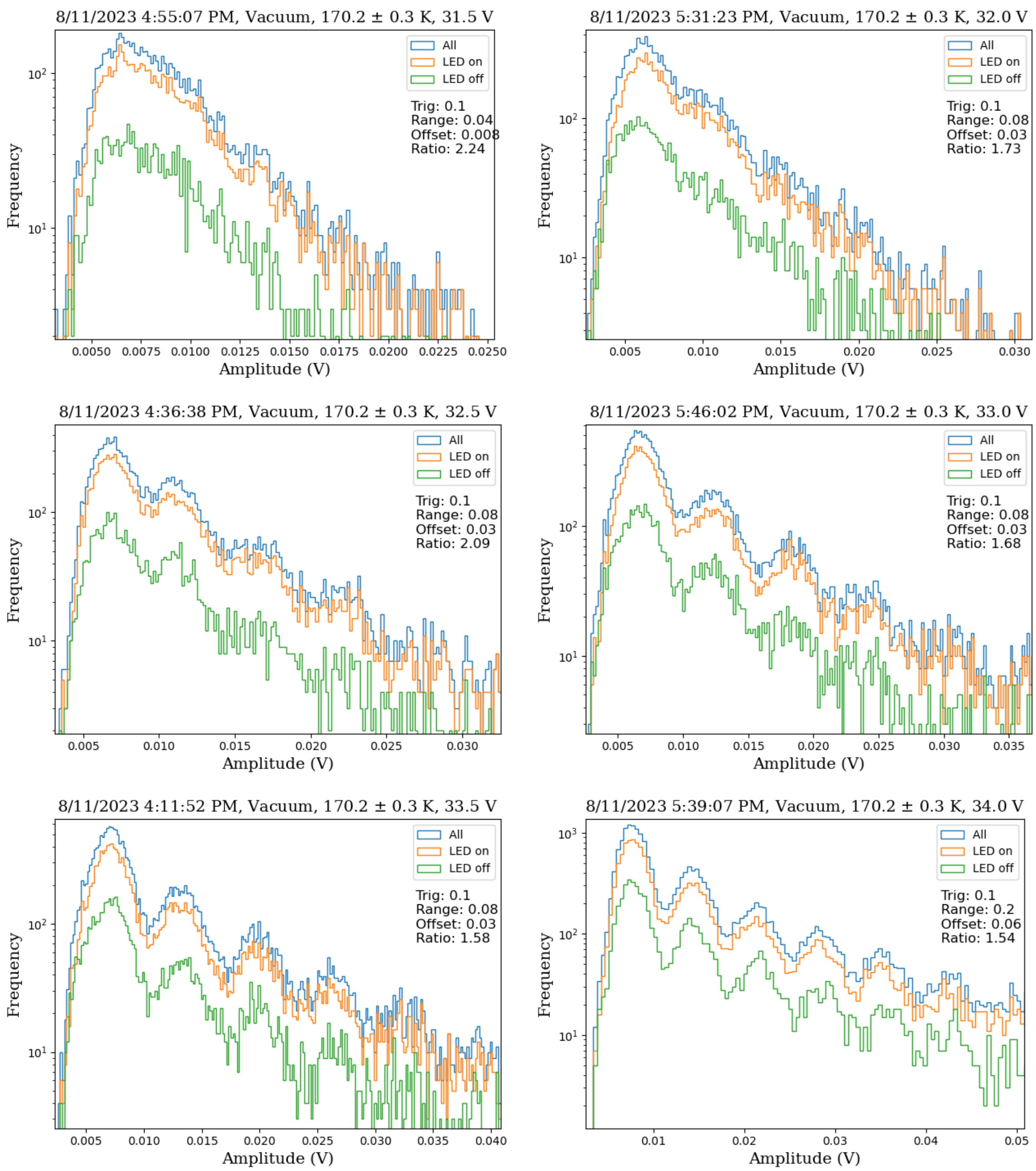


Figure 51: Six LED on/off comparison graphs (31.5-34V).

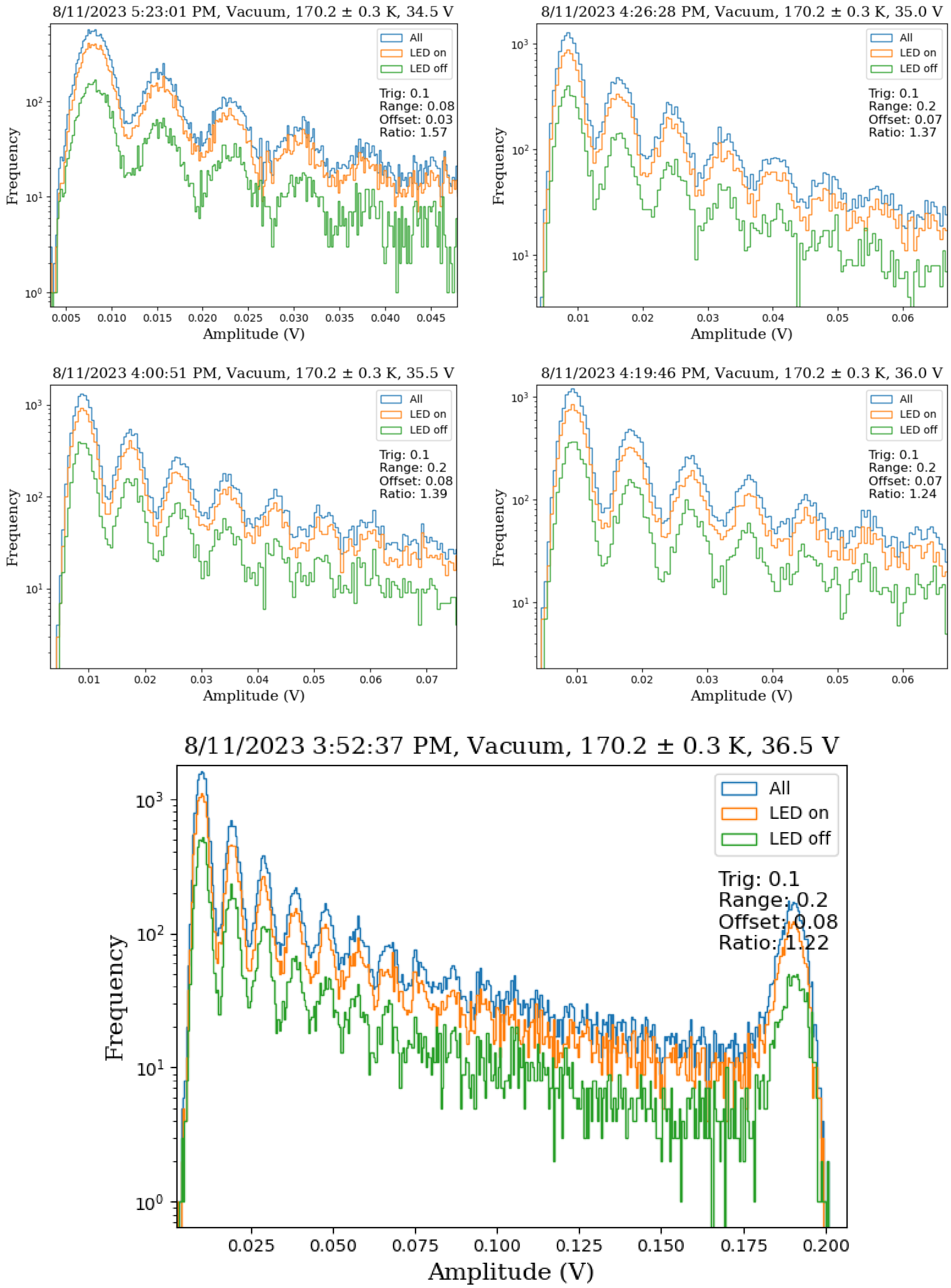


Figure 52: Five LED on/off comparison graphs (34.5-36.5V).

Multi-Gaussian Fit

A model function consisting of seven Gaussians plus a line is used to fit the histogram and determine the location of each peak in the finger plot. The error on the peak location is taken to be the standard error computed by the fit. The histogram at 31.5V, 32V, 32.5V, and 33.5V could not be Gaussian fitted.

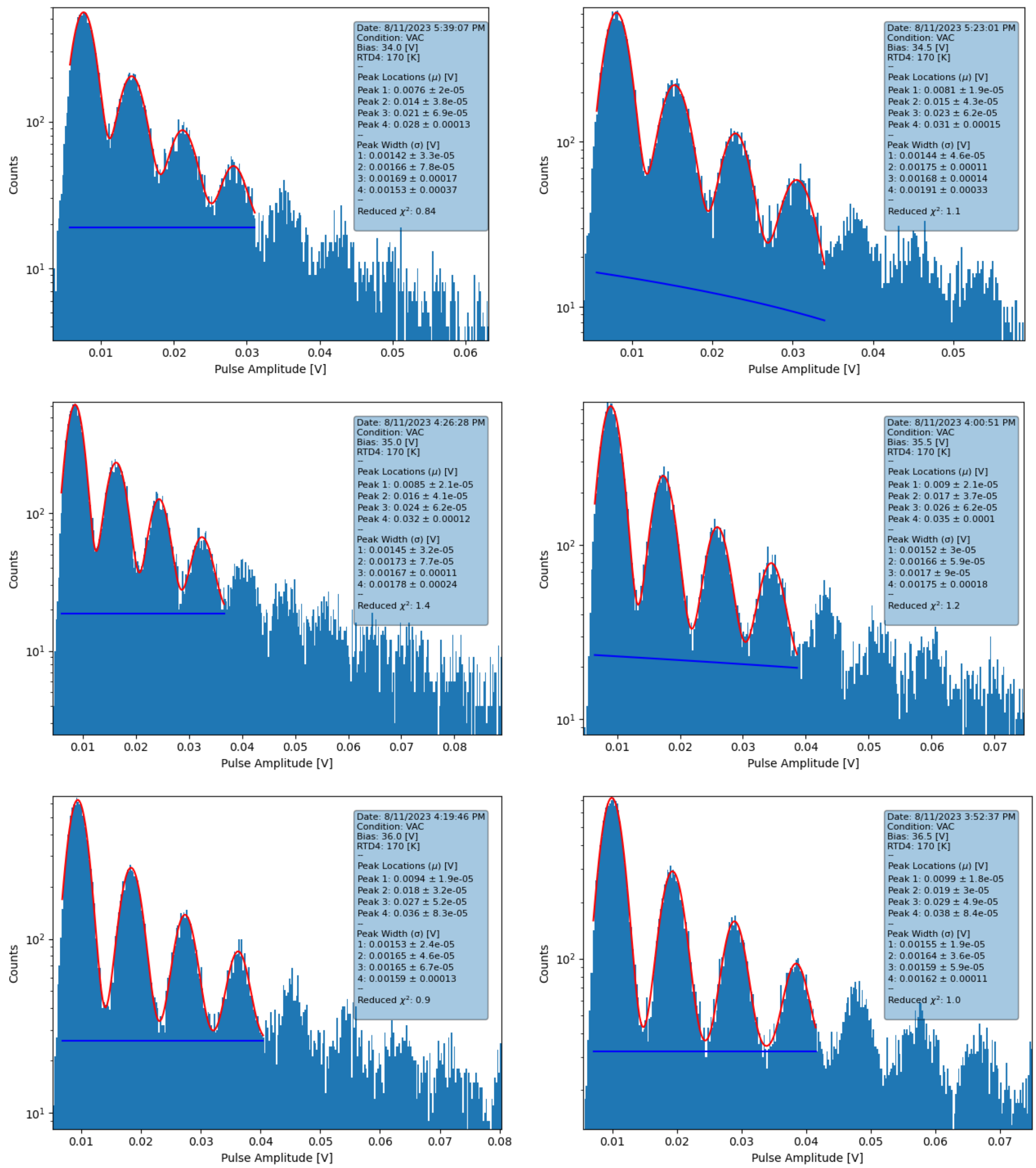


Figure 53: Six Gaussian model functions (red) plus a linear offset (blue) at each bias voltage (34V-36.5V).

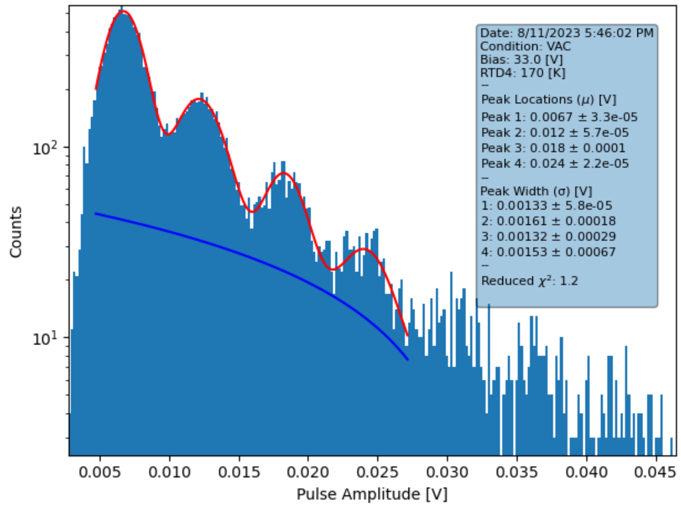


Figure 54: Gaussian model function (red) plus a linear offset (blue) at each 33 bias voltage .

Linear Fits (Average SPE Amplitude)

Using the same method as in LXe, the SPE amplitude is extracted from the plots in Figure 54 and Figure 55 by computing the difference in amplitude between each of the fingers.

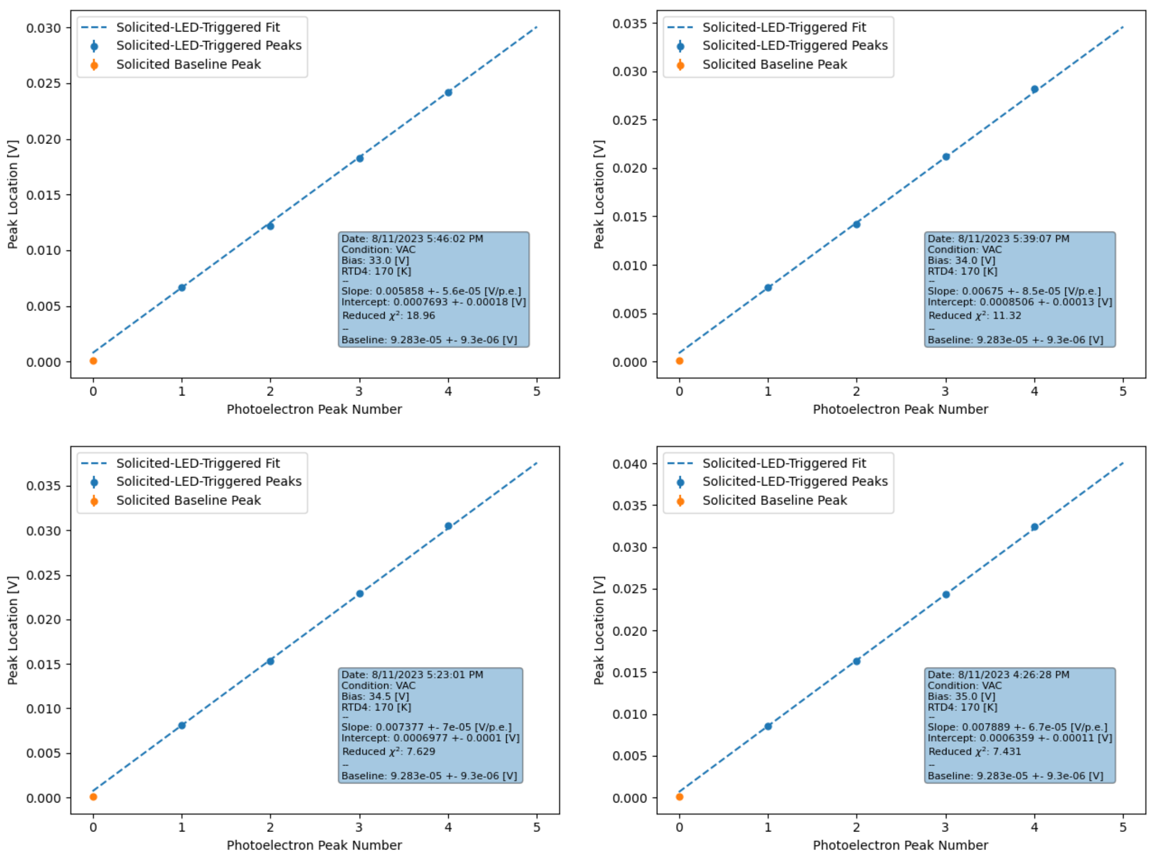


Figure 55: Four linear fits to determine average SPE amplitude at each bias voltage (33-35V), excluding 33.5V.

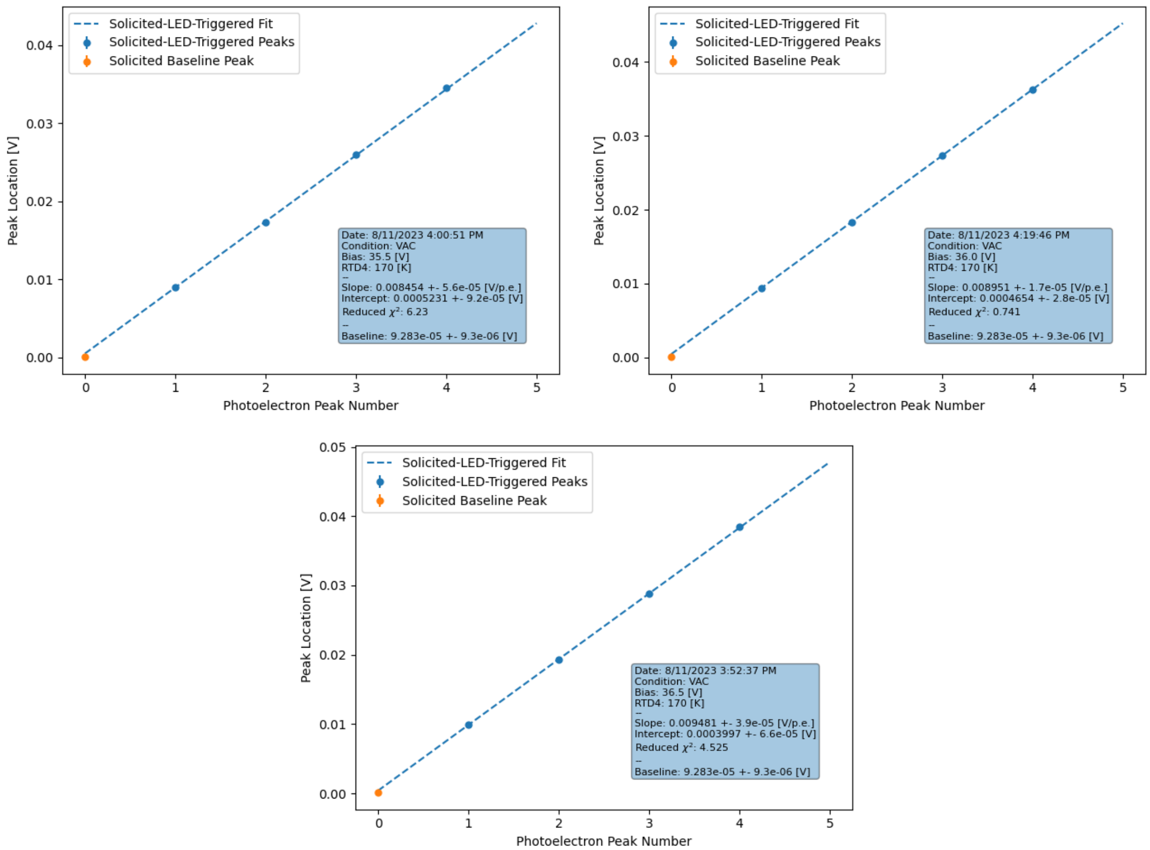
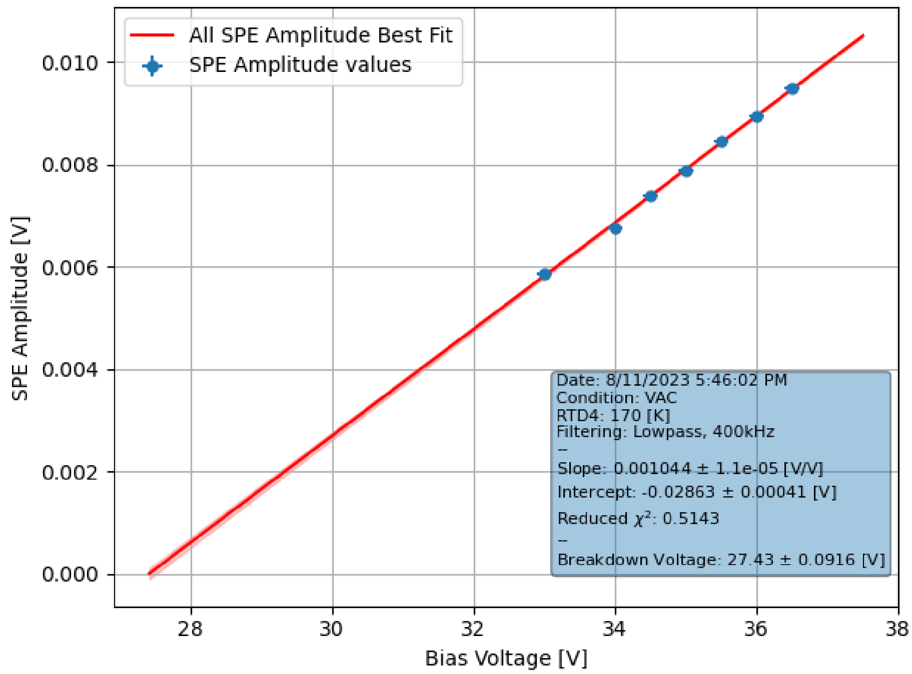


Figure 56: Three linear fits to determine average SPE amplitude at each bias voltage (35.5-36.5V).

Breakdown Voltage Calculation

The breakdown voltage is defined as the voltage after which the SiPM operates in Geiger-mode. Using the same method as in LXe, we fit a line through the data we have collected to identify the x-intercept and, thus, the breakdown voltage. The breakdown voltage was measured to be 27.43 ± 0.09 V.



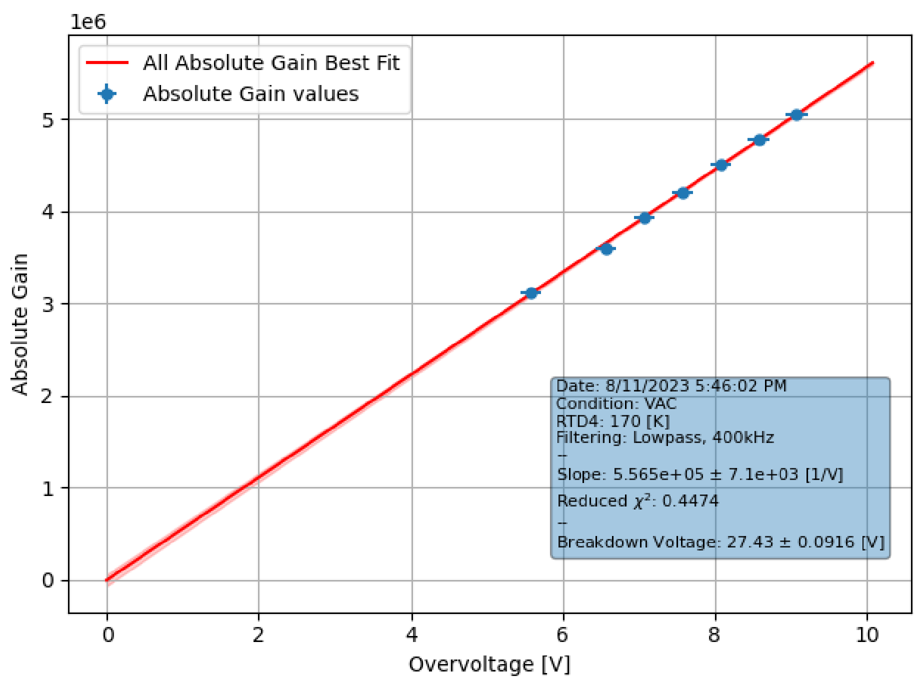


Figure 57: Linear fit to the breakdown voltage. Top: Measured SPE amplitude vs bias. Bottom: Absolute amplitude vs overvoltage.

Correlated Avalanches

Using the same method as LXe, we define the average number of correlated avalanches per activated microcell to be:

$$\langle \Lambda \rangle = \frac{1}{N} \sum_{i=1}^{N} \frac{A_i}{\bar{A}_{SPE}} - 1$$

Where A_i is the amplitude of a pulse i and $\bar{A}_{SPE}$ is the average amplitude of a pulse resulting from the activation of a single microcell ("single photon event"). As revealed in the operating voltage section, the average wave amplitudes for LED-on, LED-off, and LED-only fall within each other's uncertainty ranges. For consistency with the LXe CA and GN CA, I also used the average amplitude acquired from the LED-only histogram.

$\langle \Lambda \rangle$ for all overvoltages is found by fitting an empirical analytic function to the data:

$$\langle \Lambda \rangle = \frac{A \exp\left(B * V_{OV}\right) + 1}{A + 1} - 1,$$

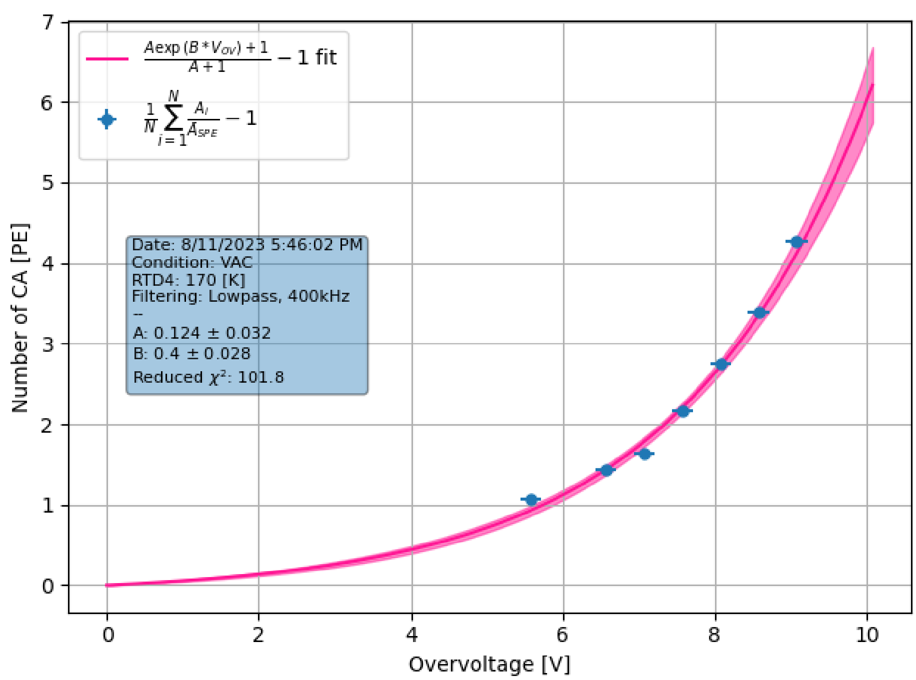


Figure 58: Correlated avalanche probability as a function of overvoltage. Horizontal error bars on the CA probability represent the error on the breakdown voltage as determined by the linear fit in Figure 57. Data taken at 170.2 ± 0.3 K in vacuum in August of 2023

CA Comparison Using Subtraction Method

By overlapping the CA data points and CA curve fit on the same graph, I want to illustrate the consistency of using the subtraction method and using the LED-only average amplitude to calculate the CA.

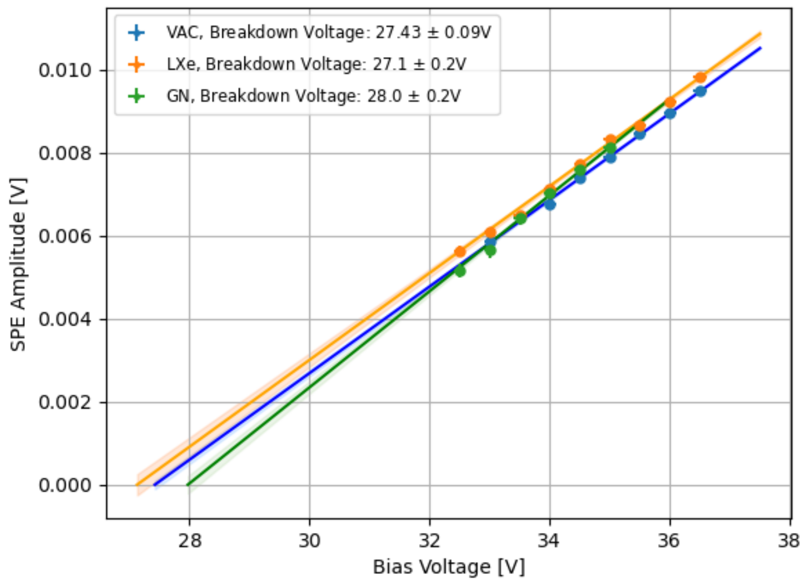


Figure 59: Linear fit to the breakdown voltage in VAC, LXe and GN. Measured SPE amplitude vs bias.

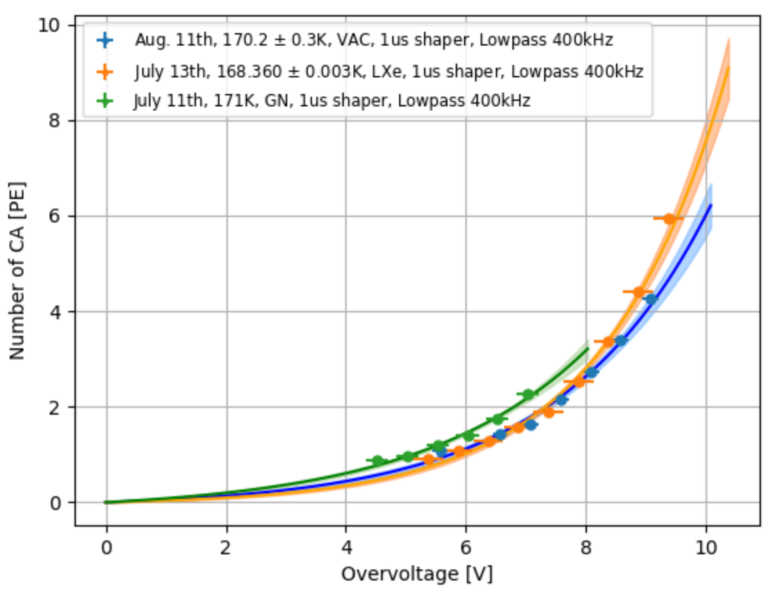


Figure 60: Correlated avalanche probability as a function of overvoltage in VAC, LXe, and GN. Horizontal error bars on the CA probability represent the error on the breakdown voltage as determined by the linear fit in Figure 59.

Inspecting the breakdown voltages in Figure 60 would explain the horizontal shift of GN in the CA comparison plot (Figure 61). This disparity is due to GN's breakdown voltage being marginally higher than that of LXe and VAC. Apart from the minor variation in overvoltage readings, the correlated avalanche curves, derived from the LED-only average amplitudes for all three media, closely overlap within their respective uncertainty margins at lower overvoltages.