Dual Calorimetry Potential of ABS and DSB Compounds

Mitchell Scholarship UVa 2024

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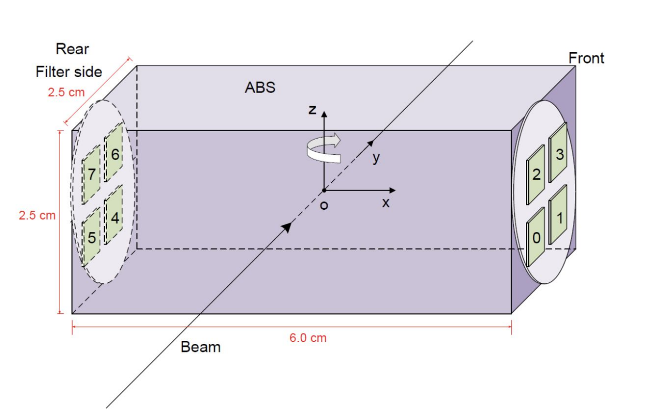
Background

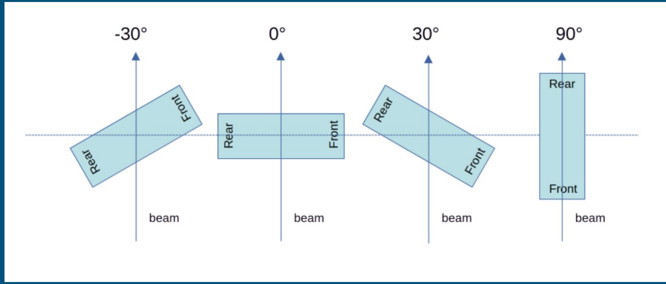
Dual Calorimetry

- Dual Calorimetry refers to the production and subsequent measurement of both normal scintillation light and Cherenkov light when particles are absorbed by a detector. Cherenkov light is produced whenever particles moving faster than the speed of light in their medium (hyper-relativistic particles) interact with the detector material.
- Accurate information about both Cherenkov and scintillation yield improves the precision of the 4-vector (momentum and energy) measurements of scattered objects in a collision.
- Up until now, dual calorimetry has been performed using a combination of Cherenkov and scintillating fibers, but this method leads to gaps in particle absorption. Prof. Hirosky's team is interested in measuring the separation of Cherenkov and scintillation light in homogeneous materials.

April 2024 Test Beam Experiment at DESY

- Earlier this year, Prof. Hirosky's team investigated the Cherenkov potential of multiple materials at the DESY test beam in Germany.
- A 2 GeV electron beam was fired at a rectangular material, with 4 silicon photomultipliers (SiPMs) on each end, corresponding to 8 channels (0-7). This apparatus was rotated between -90° and 90° with measurement sets taken at angular intervals. At least two sets of measurements were taken for each chosen angle, one for high gain and the other for low gain.
- Filters could be placed on the rear side of the material, designed to block scintillation light and thus accent Cherenkov light. Due to this, only channels 4-7 (the rear channels) exhibit noticeable effects due to filtration.





Data Organization

- The data is broken up into **<u>runs</u>**, which are measurement sets differentiated by material type, angle, etc. These are further broken into **<u>events</u>**, which house each channel response to an individual beam pulse. Thousands of events make up each run.

- There are two data sets for each event, one at a higher gain and one at a lower gain. All the raw data in this presentation is from the low gain data which are measured as negative voltage. Due to this, all the original pulses will appear negative, and all the average and normalized pulses will appear positive, although they represent the same scale.

- Channel 6 and sometimes Channel 5 malfunctioned during data taking at DESY. Therefore they are omitted from plots and analysis in this presentation.

The Glasses and this Investigation

My investigation this summer focused on 2 glass compounds tested at DESY, ABS Z-L and DSB-3. These glasses were designed specifically as homogenous dual calorimetry materials, and their first test was at DESY earlier this year. As a consequence, this is the first study of these materials. The potential advantage of these materials is low cost, as they are much cheaper than crystals. The goal this summer was to answer two questions. Are Cherenkov and normal scintillation light present and separable in these glasses? If so, how much can be measured?

ABS L-Z (Aluminoborosilicate)

- Chemical Formula: B_2O_3-SiO_2-Al_2O_3-Gd_2O_3-Ce_2O_3
- Dimensions: 25 x 25 x 60 mm^3
- Filter (when applied to rear): 610 nm - 3mm thick

DSB-3 (Barium Di-silicate)

- Chemical Formula: BaO-$2SiO_2$-Gd_2O_3-Ce_2O_3
- Dimensions: 20 x 20 x 150 mm^3
- Filter (when applied to rear): 640 nm - 1mm thick

First Question:

Are Cherenkov and Scintillation Light Present?

Strategy

The key to finding the presence of Cherenkov and scintillation light is to identify their shape in the SiPM response waveform. This was done using the steps below.

1) Look at the first few events in a run to identify a basic trend
2) Align the timing for the electron beam activation in each event
3) Cut out invalid events from the analysis
4) Calculate an average pulse to show what the general SiPM response is
5) Normalize the average pulse to identify the SiPM response shape

<u>Cherenkov Pulse Shape</u>

Cherenkov pulses are characterized by an immediate rising edge leading up to a sharp peak, followed by a quick decay.

<u>Regular Scintillation Pulse Shape</u>

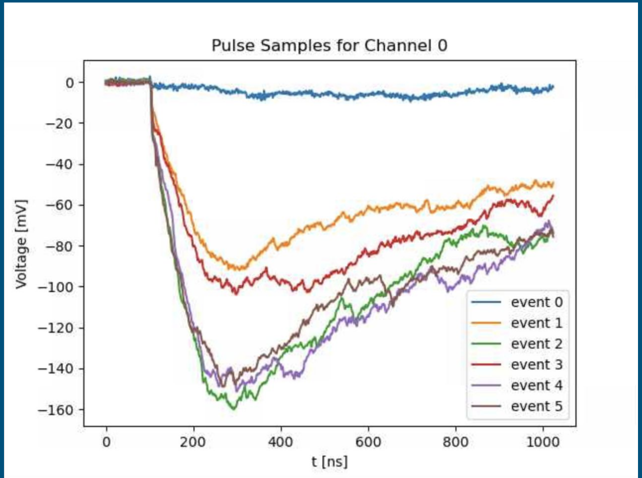
Regular scintillation pulses are characterized by a gradual ascent to a curved peak, followed by slower logarithmic decay (as compared to cherenkov).

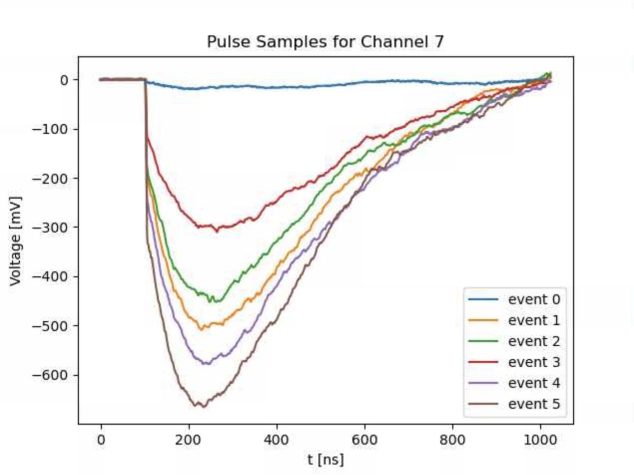
First Look

To the right are the first 6 events of the 90° unfiltered ABS run for channels 0 and 7. They are examples of a sanity check to make sure nothing incredibly unexpected was happening.

These events have a single peaked curved pulse which is expected considering that there is one electron beam pulse, which should cause a voltage peak and decay response in the glass.

There are also events such as event 0 which produce no meaningful response and need to be removed to preserve an accurate average pulse shape.





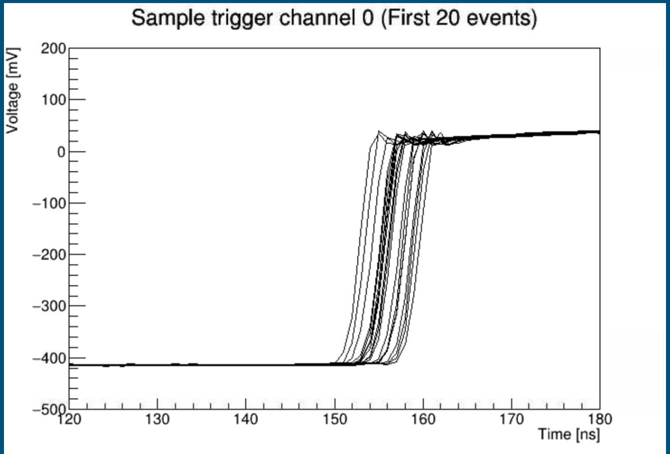
Trigger Alignment

To the right are the zoomed in electron trigger beam pulses for the first 20 events in the 90° unfiltered ABS run.

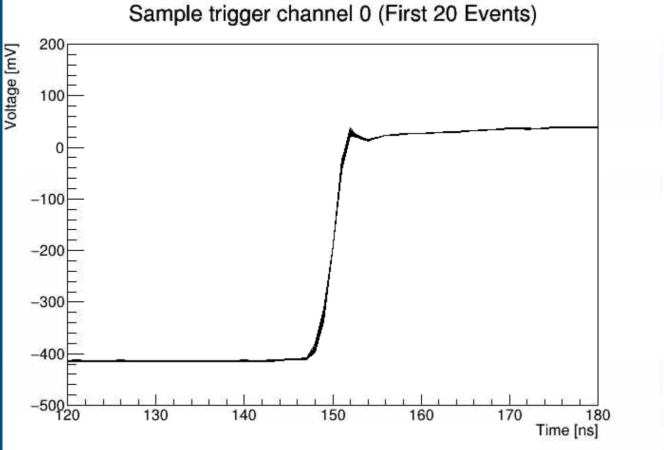
As shown, these pulses vary by about 10 ns, requiring an alignment procedure before calculating the average pulse. This was done by taking the midpoint of the rising edges (halfway between peak and pedestal), and lining them up at 150 ns, shifting every data point in the event with it (this includes both trigger pulse and material response pulse).

However, the data points are 1 ns apart, so in order to make the error in the trigger alignment less than 1 ns, linear interpolation was needed.

Before Trigger Alignment



After Trigger Alignment

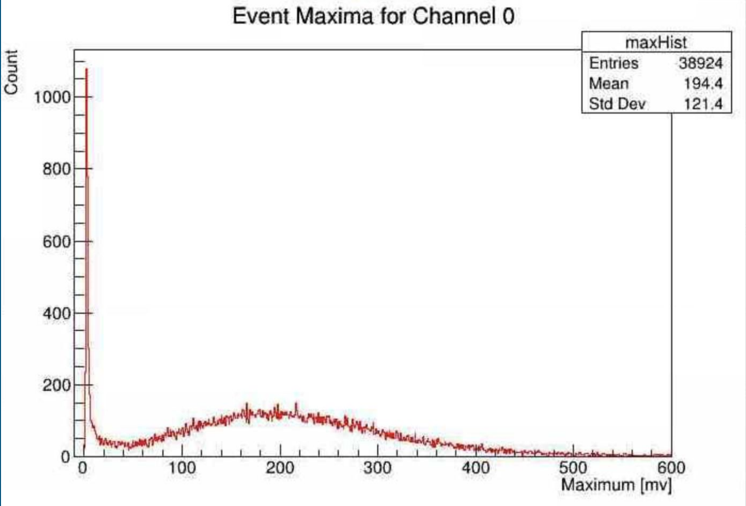


Cuts

As shown before, many events in a run are duds, and they can be identified by their peak voltage. They need to be removed from the average calculation because they might skew the shape of the result. The histogram to the right shows the distribution of peak voltages for the 90° filtered ABS across each event in channel 0.

Note that the sharp peak on the left of the plot indicates faulty runs. For each run, I made plots for each channel like the one on the right, and chose a mV cut to eliminate the leftmost peak while preserving the general shape of the distribution.

The table to the right shows the cuts made to the runs that are relevant to the next 3 slides.

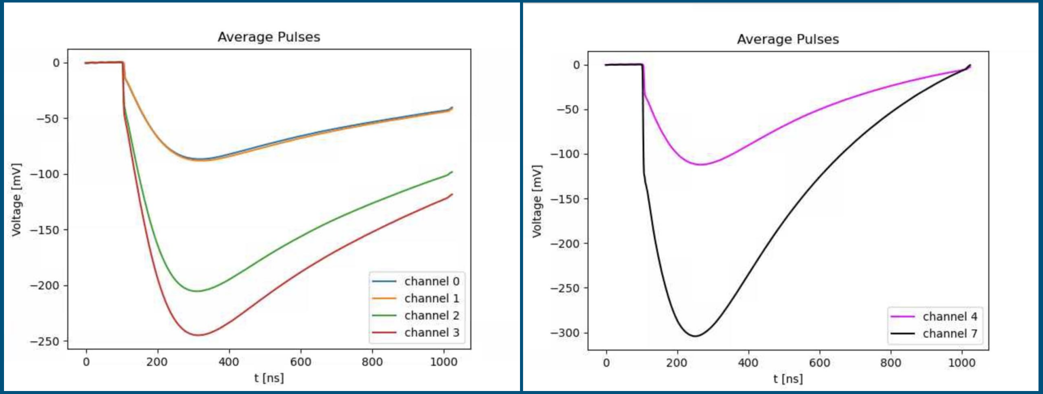


Run	Cut Events with Maxima Less than [mV]
ABS 90°	15
ABS Filtered 90°	5
DSB 60°	5
DSB Filtered 60°	5

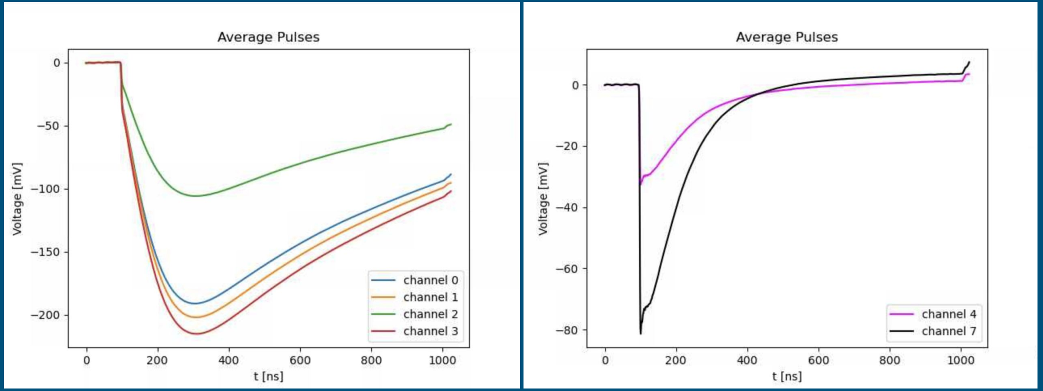
ABS Average Pulses

The average pulses on the right show each of the functioning ABS channels at 90° with and without a filter.
Without the filter, we can already see the sharp rising cherenkov edge leading up to the curved scintillation shape. With the filter, the Cherenkov shape is completely isolated in the rear channels (where the filter is).

Unfiltered ABS



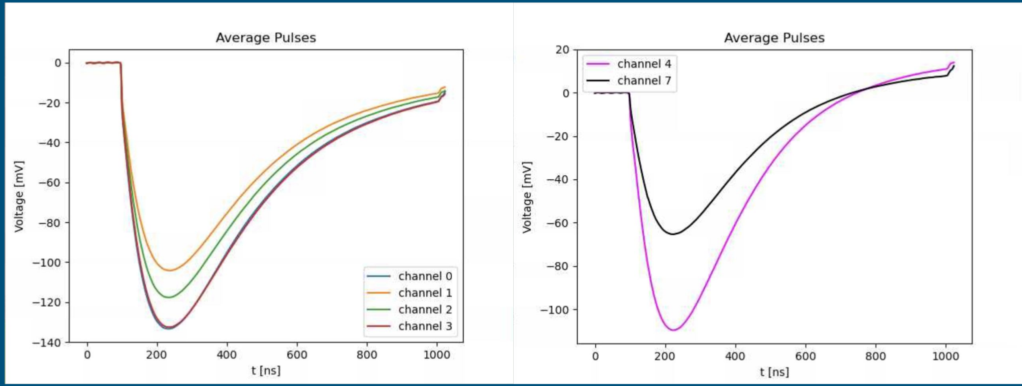
Filtered ABS



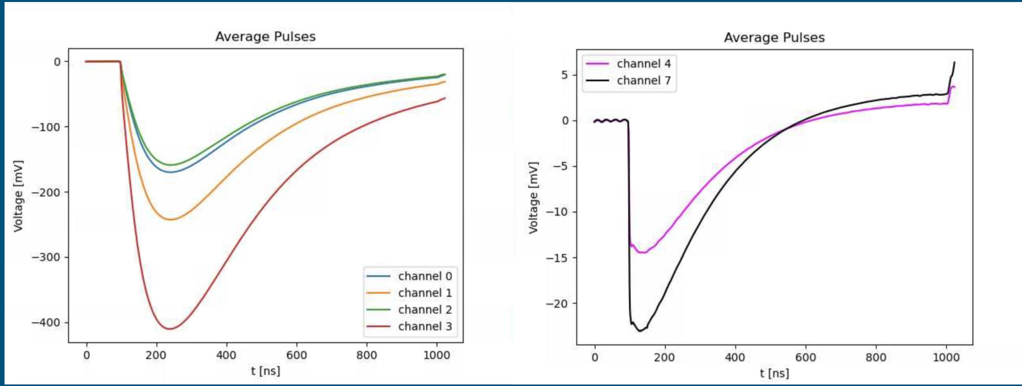
DSB Average Pulses

The average pulses on the right show each of the functioning DSB channels at 90° with and without a filter.
Without the filter, it is difficult to see any Cherenkov response within the glass. After applying the filter, the rear channels do show some Cherenkov response, but the scale between the top and bottom graphs gives an idea of how small the response might be.

Unfiltered DSB



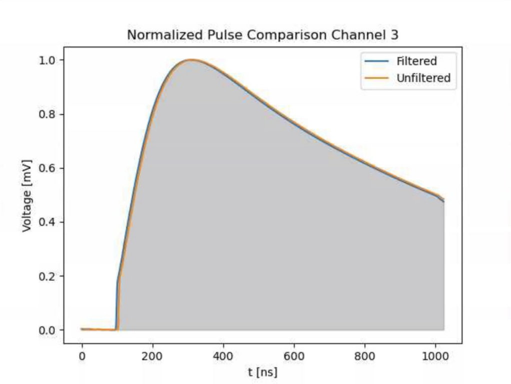
Filtered DSB



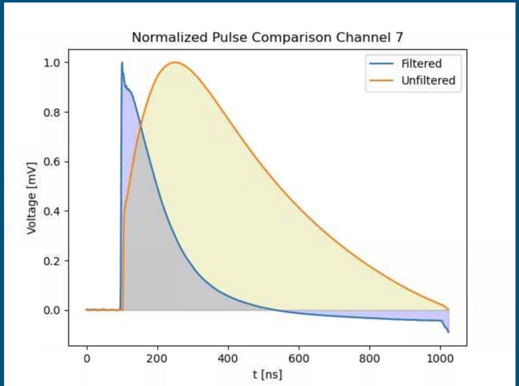
Normalized Pulses

The normalized pulses on the right show the filtered and unfiltered shapes overlaid on each other for the front and rear of the 90° glasses.
As expected, the filter has no effect on the shape of the pulse on the front of the glasses.
On the rear of ABS, the filters cut out almost all of the scintillation light and leave a clean Cherenkov shape. On the rear of DSB, the filter still isolates Cherenkov light, but leaves a little more scintillation residue.

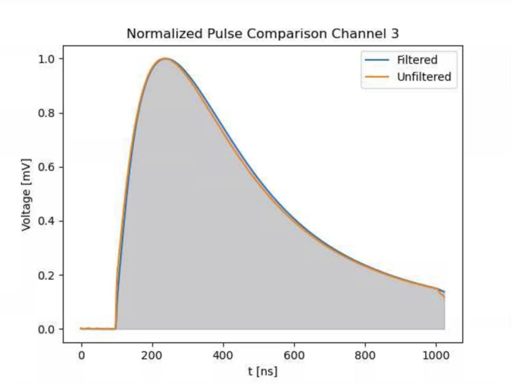
ABS Front



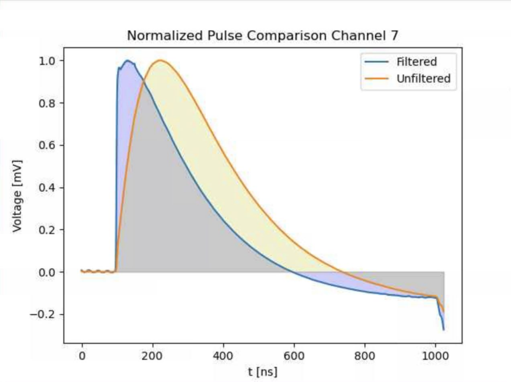
ABS Rear



DSB Front



DSB Rear



First Conclusions

Both glasses have a separable component of Chenkov light within their scintillation response. ABS seems to have a larger Cherenkov component (relative to scintillation light) than DSB that is easier to isolate. However, this could be due to many factors, such as the length or density. The ABS glass is shorter and denser than DSB, which will have an effect on the displacement of the energy deposition relative to the SiPM. Future investigation would have to make the dimensions consistent, and have a better understanding of the effects of density to make more precise conclusions.

Another takeaway from these plots is that the difficulty with these materials will be finding the Cherenkov within the scintillation light, not the scintillation light within the Cherenkov. The next part of the investigation looks at quantifying the amount of Cherenkov present, so that we know if there is enough to be useful.

Second Question:

How Much Cherenkov Light is Present?

Strategy

Eventually, it would be good to get to a point where we can compare different SiPMs with quantitative measurements. This would involve a detailed calculation of how many photons are being detected by the SiPM. Before that though, we need to know how many photoelectrons are being produced by the SiPM. The calculation for that includes the following steps:

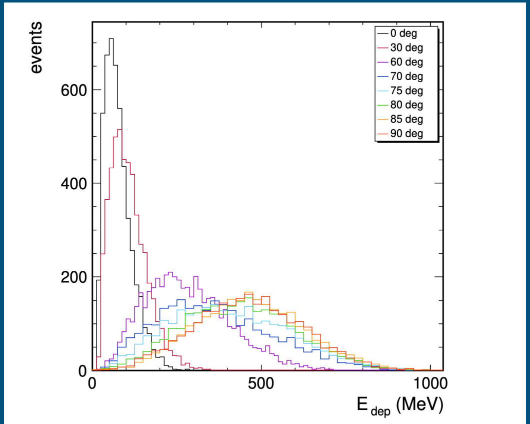
1) Find an isolated Cherenkov waveform and quantify qualities of its shape
2) Adjust the magnitude of the average pulses to show the pulse shape at full energy deposition.
3) Use the previously identified Cherenkov pulse shapes to reveal the Cherenkov peaks amidst scintillation light dominated runs
4) Convert peak Cherenkov voltage to photo-electron count

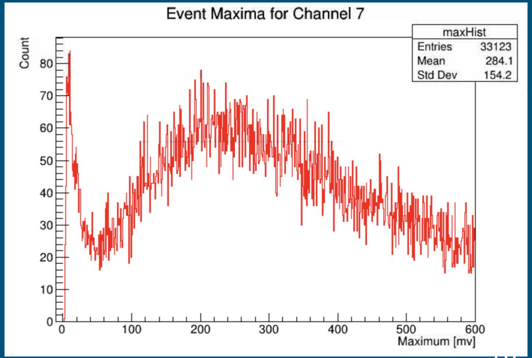
Energy Deposition

With the exception of the failed events, the distribution of pulse maximums correspond to the distribution of energy deposition by the electron beam in the glass. Because of this, the most popular maximum corresponds to the maximum I want to find the photon count of.

To the top right is the ABS Energy Deposition for a 2 GeV electron beam at different angles. It was generated by Alexander Ledovsky, using a Geant4 simulation. The peak of the 90 line on that plot corresponds to the peak of the histogram on the bottom right, which is the measured maximum for ABS at 90°.

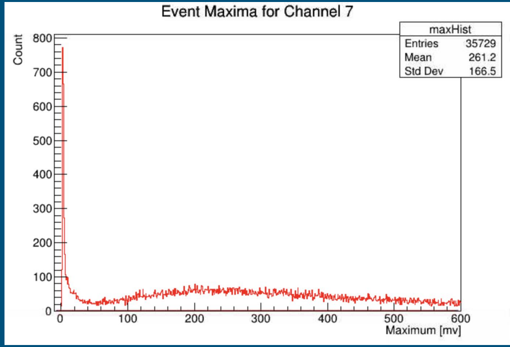
ABS Energy Deposition

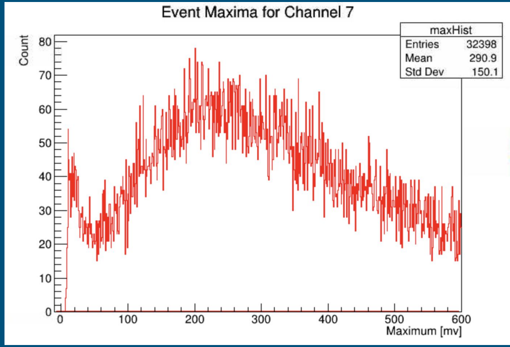




A Note on New Cuts

This time, I made a different cut to eliminate the left hand peak of the maximum histograms that is more automatable. I only included events with maximums 10x greater than the RMS of the noise (the noise being the portion of the pulse before the trigger turns on). The plots below are an example of the affects. On the left is before the cut and on the right is after the cut.

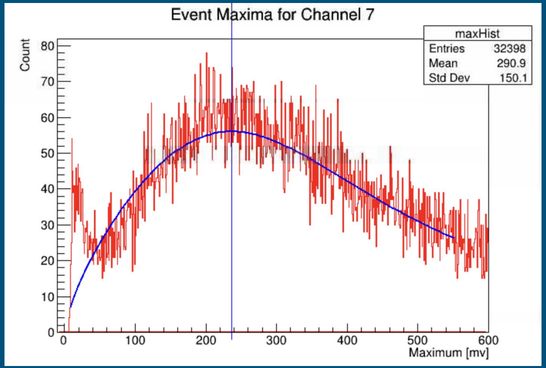




Energy Deposition - Finding the Common Maxima

$$f(x) = \frac{Ax^B}{C+Dx^E}$$

In order to find the most common maximum automatically, I needed a way to eliminate static, otherwise a statistically unlikely bin might skew my maximum. As a consequence, I used the formula to the right to fit each maximum histogram (With A, B, C, D, and E being fit parameters). I used the maximum of this fit as representing full energy deposition.



The plot to the right is an example of one of these fits, with the vertical line representing the most common maximum.

For the rest of this investigation, pulse plot are normalized to their most common maximums.

Rising Edge to Peak Cherenkov Ratio

In order to determine the number of photoelectrons produced by Cherenkov light, we need the Cherenkov pulse peak, but it is not always obvious where the peak is located when scintillation light is also present. One thing that is always present, even with scintillation light, is the Cherenkov rising edge. This edge can be identified by taking the derivative of the original pulse, the peak of which is the point of maximum change in the undifferentiated signal.

The ratio of the Cherenkov pulse peak and point of maximum change should be constant for any channel in any run, considering the Cherenkov shape stays constant. Using a run of pure Cherenkov light, this ratio can be calculated from measured values. Then the ratio of the Cherenkov pulse peak and point of maximum change can be applied to a run with scintillation light present to calculate an unknown pulse peak from a known point of maximum change.

Rising Edge to Peak Cherenkov Ratio (Continued)

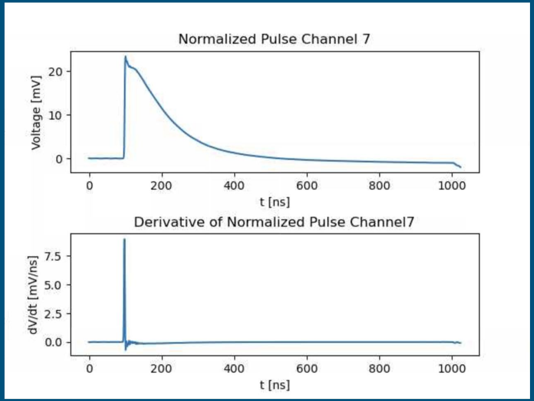
The filtered ABS channel 7 at 90° shown to the right is an exclusively Cherenkov pulse, normalized to its maximum energy deposition. Its original pulse and derivative are shown twice (the bottom having higher magnification). The green line on the right shows the peak of the Cherenkov pulse. The red line shows the same position in time on the derivative as on the original graph, because it corresponds to the point of fastest increase.

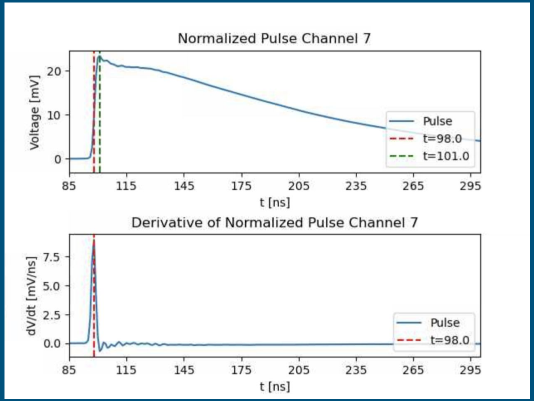
Dividing the voltage of the peak (green) by the voltage of the point of fastest increase (red), I calculated the following ratio.

Voltage at Point of Fastest Increase = 8.9458 mV

Cherenkov Pulse Peak = 23.3820 mV

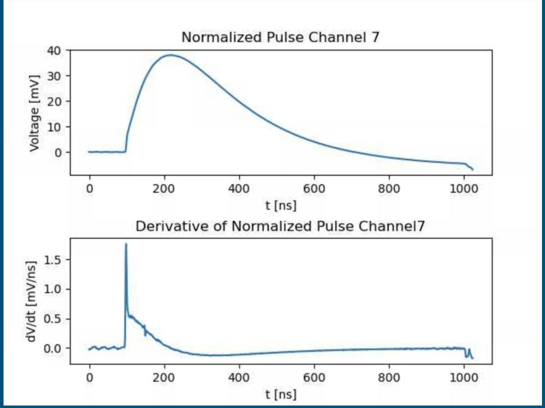
Ratio = 2.6137





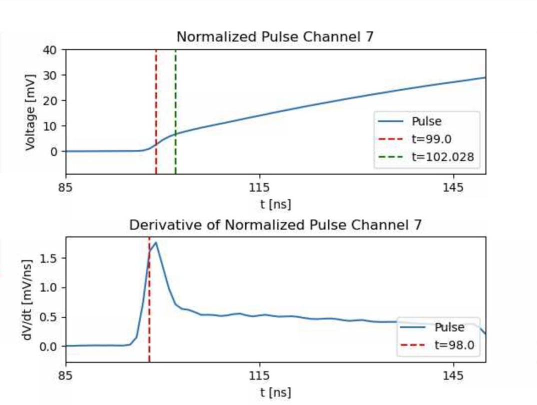
Determining a Cherenkov Maximum

To the right is the Channel 7 of an unfiltered run of DSB glass at 0°, which notably has a very small and hard to find Cherenkov component. The bottom plot, like the previous slide, is a higher magnification of the top. The red line in the figures represents the time of fastest increase.



(Voltage at Fastest Increase) x (Ratio) = (Cherenkov Pulse Peak)

2.559 mV x 2.6137 = 6.6875 mV



Using the ratio determined from the pure Cherenkov pulse in the previous slide, I was able to predict what the Cherenkov pulse would be in mV, and find the time at which that mV occurs. This is represented in the green line to the right.

Converting mV to Photoelectron Count

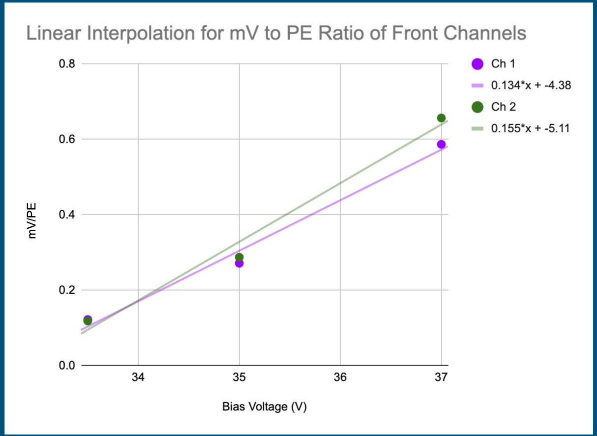
During the DESY test beam experiment, Professor Hirosky took SiPM calibration measurements for each channel, which he converted into a mV to photoelectron count (mV/PE) ratio. These ratios take into account the gain of each SiPM, which depends on the bias voltage (the control voltage used to increase or decrease a signal) and the temperature. His original table is below, and the full presentation is linked in the references slide (which includes the temperature).

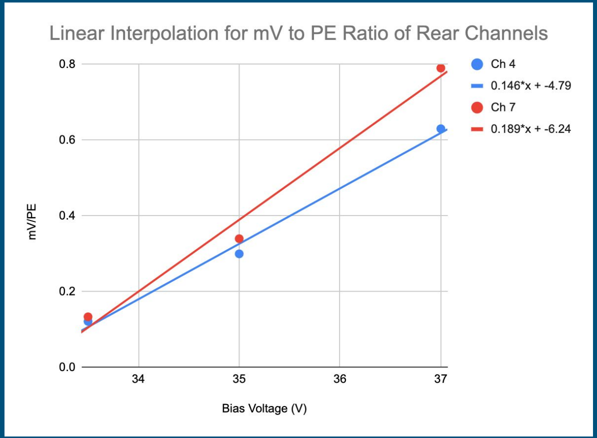
	Channel mV/PE			
Voltage Bias	1	2	4	7
33.5	0.123	0.119	0.122	0.134
35	0.272	0.288	0.30	0.34
37	0.587	0.657	0.63	0.79

Only front channels 1 and 2 were used in this portion of the study, because they correspond to the functional rear channels, 4 and 7.

mV to PE Count (Continued)

Unfortunately, the table from the previous slide does not include all of the bias voltages used for runs in this study. To remedy this, linear interpolation was needed, the graphs for which are to the right. The new mV/Pe ratios are given in the below table.





	Channel mV/PE (Interpolated)			
Voltage Bias	1	2	4	7
34.5	0.243	0.238	0.247	0.281
36	0.444	0.47	0.466	0.564
40	0.98	1.09	1.05	1.32

Filtered vs Unfiltered Cherenkov Count

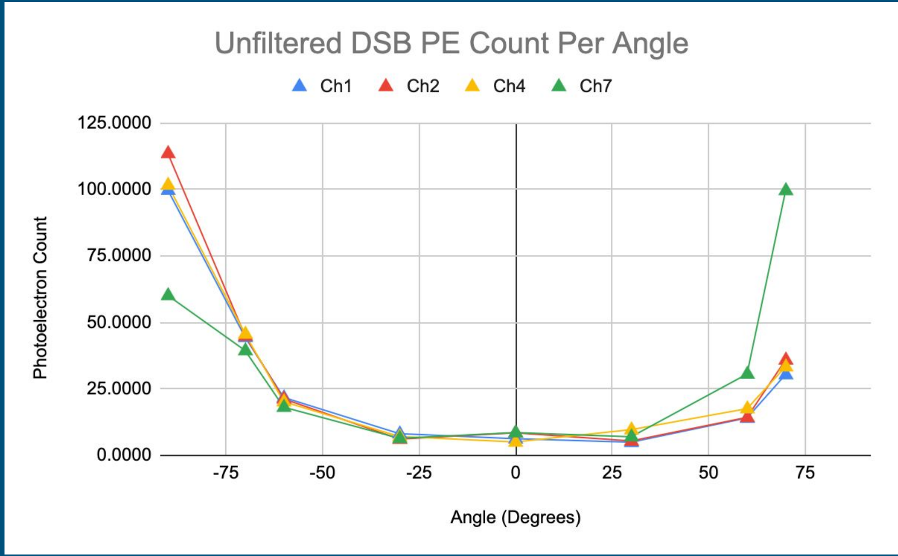
After completing a photoelectron count calculation, here is a test of its effectiveness. To the right is a table of Cherenkov PE count for filtered and unfiltered runs in ABS and DSB as well as the percentage PE loss when the filter is applied.

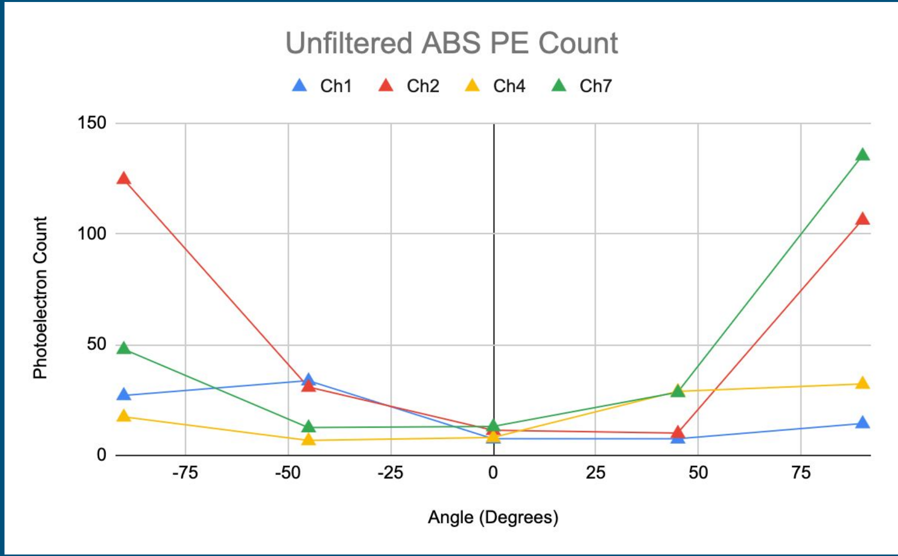
Notice that the percentage loss for -90° DSB at Channel 1 is negative, which is non-physical. This may have started as an error in the Cherenkov Maximum determining process, but it is compounded by the errors in the voltage bias calculation, and given that the unfiltered voltage bias was 33.5V, the mV to PE ratio is an extrapolated value prone to more errors.

		PE Count		
	Channel	**Unfiltered**	**Filtered**	**Percentage Loss**
90 Degree ABS	1	106.1815	44.8707	57.74%
	2	32.0910	20.7463	35.35%
	3	135.1502	14.2618	89.45%
	4	110.3724	19.0370	82.75%
-90 Degree DSB	1	99.6577	110.3724	-10.75%
	2	113.4731	77.1836	31.98%
	3	101.5746	16.9471	83.32%
	4	60.0330	13.2932	77.86%

On the whole, this method shows that there is more Cherenkov loss in the rear channels than the front channels, which is expected.

An Additional Study in Angle for Unfiltered Runs





Above is another study that shows the PE count per angle of rotation. A parabolic shape is expected because Cherenkov light emanates in a cone pattern (rather than being spherically symmetric, like normal light), and so the angles closest to 90° and -90° should respond the most. The plots above show this shape generally, but we specifically expect the rear channels to respond the most at 90° and the front channels to respond at 90°, which is not represented in these plots.

Second Conclusions and Moving Forward

The trends in filtration and angle for the PE study seem representative of reality, but the specific numbers show errors in the calculations. I conclude that this study shows a qualitatively significant photoelectron count calculation method, but is held back from being quantitatively accurate.

The first of the main errors is the Cherenkov peak characterization, which would benefit from a more sophisticated fitting technique, rather than relying on the single ratio of point of fastest increase to peak.

The second of the main errors is the interpolation of mV to PE count ratios. I would recommend that future experimentation and analysis stick as close as it can to measured ratios.

References

Large Size ABS and DSB Scintillating Glass Samples, *Ren-Yuan Zhu*

https://cernbox.cern.ch/pdf-viewer/public/6qFY9v2DBhGddVn/4Calvision_240118_ABS_DSB_glass.pdf

DESY TB Calibrations 1, *Robert Hirosky*

https://docs.google.com/presentation/d/1B6rZCADIirXo_n6jqyACmOyxZXbCdbT7LqyV0iO0ink/edit#slide=id.p

TB Update (June 14, 2024), *Alexander Ledovsky*

https://indico.cern.ch/event/1427803/contributions/6005430/attachments/2878333/5041263/240614_calvision_ledovskoy.pdf

Photoelectron Calculations and Counts

Filtered vs Unfiltered Cherenkov Count

(Data Table)

		Bias Voltage (V)	Peak Voltage (mV)	PE Count
90 Degrees ABS Filtered Run# - 350	Ch1	36	19.9226	44.8707
	Ch2	36	9.7508	20.7463
	Ch4	40	14.9749	14.2618
	Ch7	40	25.1289	19.0370
90 Degrees ABS Unfiltered Run# - 311	Ch1	36	6.3248	14.2451
	Ch2	36	49.9053	106.1815
	Ch4	36	14.9544	32.0910
	Ch7	36	76.2247	135.1502
-90 Degrees DSB Filtered Run# - 186	Ch1	34.5	26.8205	110.3724
	Ch2	34.5	18.3697	77.1836
	Ch4	37	10.6767	16.9471
	Ch7	37	10.5016	13.2932
-90 Degrees DSB Unfiltered Run# - 178	Ch1	33.5	12.2579	99.6577
	Ch2	33.5	13.5033	113.4731
	Ch4	33.5	12.3921	101.5746
	Ch7	33.5	8.0444	60.0330

ABS Unfiltered Runs

		Bias Voltage (V)	Peak Voltage (mV)	PE Count
45 Degrees ABS Unfiltered Run# - 314	Ch1	36	3.27676	7.38009009
	Ch2	36	4.66336	9.922042553
	Ch4	36	13.3942	28.74291845
	Ch7	36	15.9583	28.29485816
0 Degrees ABS Unfiltered Run# - 317	Ch1	36	3.28131	7.390337838
	Ch2	36	5.2661	11.20446809
	Ch4	36	3.69686	7.933175966
	Ch7	36	7.26929	12.88881206
-45 Degrees ABS Unfiltered Run# - 319	Ch1	36	14.923	33.61036036
	Ch2	36	14.4446	30.73319149
	Ch4	36	3.09183	6.634828326
	Ch7	36	6.99179	12.39679078
-90 Degrees ABS Unfiltered Run# - 321	Ch1	36	11.946	26.90540541
	Ch2	36	58.5119	124.4934043
	Ch4	36	8.04346	17.26064378
	Ch7	36	26.9542	47.79113475

DSB Unfiltered Runs <= 0°

		Bias Voltage (V)	Peak Voltage (mV)	PE Count
-70 Degrees DSB Unfiltered Run# - 175	Ch1	35	12.0476	44.29264706
	Ch2	35	12.9022	44.79930556
	Ch4	35	13.6615	45.53833333
	Ch7	35	13.3777	39.34617647
-60 Degrees DSB Unfiltered Run# - 171	Ch1	37	12.7014	21.63781942
	Ch2	37	13.8771	21.12191781
	Ch4	37	12.6329	20.05222222
	Ch7	37	14.2368	18.02126582
-30 Degrees DSB Unfiltered Run# - 167	Ch1	37	4.70194	8.01011925
	Ch2	37	3.94335	6.002054795
	Ch4	37	4.38985	6.968015873
	Ch7	37	4.97077	6.292113924
0 Degrees DSB Unfiltered Run# - 150	Ch1	37	3.59168	6.118705281
	Ch2	37	5.47914	8.339634703
	Ch4	37	3.10077	4.921857143
	Ch7	37	6.68752	8.46521519

DSB Unfiltered Runs > 0°

		Bias Voltage (V)	Peak Voltage (mV)	PE Count
30 Degrees DSB Unfiltered Run# - 155	Ch1	37	2.82453	4.811805792
	Ch2	37	3.47642	5.291354642
	Ch4	37	6.02508	9.563619048
	Ch7	37	5.42742	6.870151899
60 Degrees DSB Unfiltered Run# - 158	Ch1	37	8.1783	13.93236797
	Ch2	37	9.30731	14.16637747
	Ch4	37	10.9974	17.45619048
	Ch7	37	24.0701	30.46848101
70 Degrees DSB Unfiltered Run# - 163	Ch1	36	13.446	30.28378378
	Ch2	36	16.8198	35.78680851
	Ch4	37	20.9277	33.21857143
	Ch7	37	78.6479	99.5543038