Phys 393
Long-Term Response of Vacuum Photo-Triodes

John Christopher Jones

Fall 2008

Abstract

The CMS experiment at CERN uses vacuum phototriodes (VPTs) in the electrocalorimetery layer of the endcap section of the CMS detector. They are hardened against the extreme radiation found in the endcap section a Large Hadron Collidor detector, while remaining cost effective. However, their long-term performance is still not well understood. In this paper, we explore the results of a long term study undertaken by the UVA CMS group in the Fall of 2008.

Contents

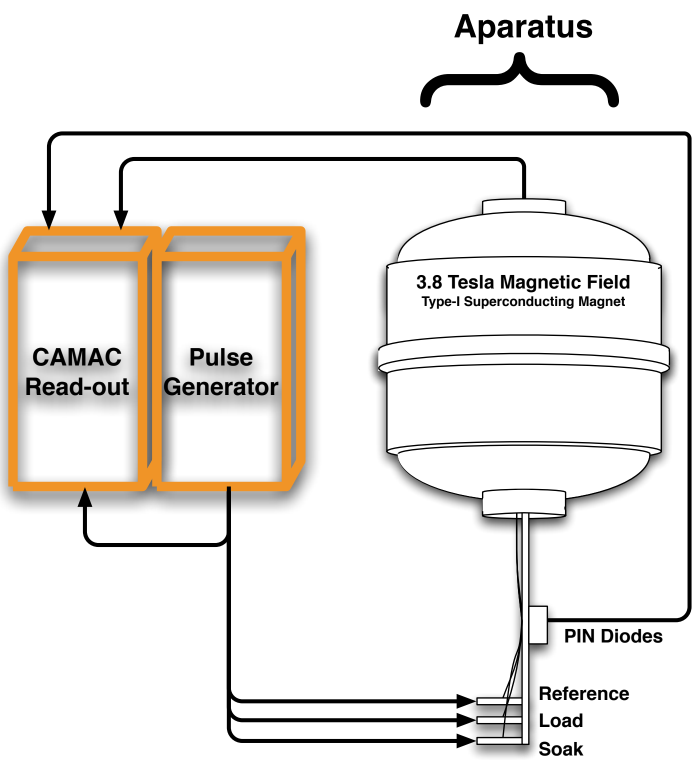


Figure 1: Overview of Experimental Setup

1 Introduction

The long term exponential decline of the cathode current of several (e.g., six) VPTs will be measured over two to five days and projected out to several years.

One question which needs to be answered is whether the current decays to some measurably significant magnitude. To answer this question, the current decay will be treated as a series of exponential decays, and the behavior of the "decay constant" will be examined to see if it approaches some constant value. If the "decay constant" approaches a constant value over time, that will imply that the VPTs' gain approaches zero, which will compromise the long-term viability of VPTs for electrocalorimetery in the end caps of CMS. The VPTs will be measured starting with 10 nA cathode current at an angle of 15 degrees to the magnetic field, a nominal angle of the VPTs in the endcap of CMS. To determine how long the VPTs may remain viable if the decay is constant, a long-term measurement will be made to calibrate a time projection.

2 Experimental Setup

The experimental setup is divided into three main sections: (1) the apparatus itself, (2) a pulse generator, and (3) data recording. Figure 1 shows this conceptually, but there is some bidirectional communication between the pulse generator (Section 2.2) and the CAMAC crate (Section **??**).

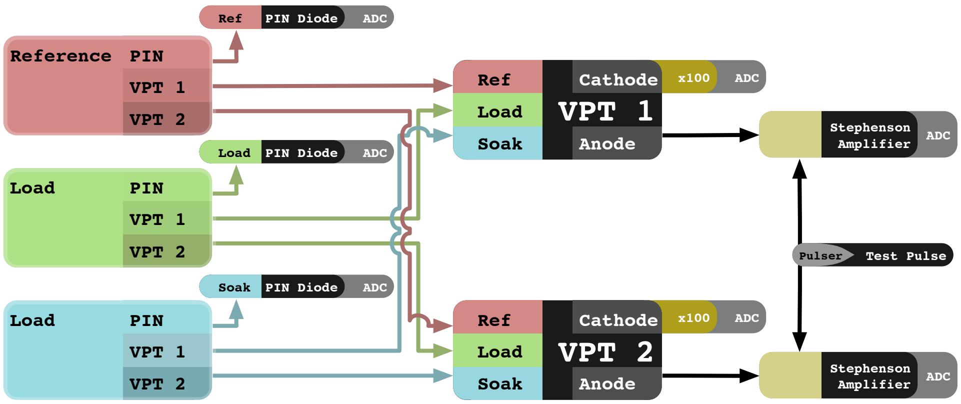


Figure 2: Summarized Aparatus Signal Path

2.1 Experimental Aparatus

The experimental aparatus is logically centered on two VPTs placed in the center of a uniform magnetic field of 3.8 T. Mostly outside the field ($\sim$0.1 T), three LEDs which emit blue monochromatic light (Lumileds Luxeon III LXHL-PR09) are controlled by the Pulser (Section 2.2). These LED light sources are referred to as the Reference, Load, and Soak LEDs. The light is focused into three polymer fiber optic cables (1.5 mm plastic fiber from Fiber Optic Products) per LED, for a total of nine fibers. For each LED, one fiber goes to each of the PIN Diode, VPT 1, and VPT 2. Each LED has its own dedicated PIN Diode, which is read by the ADC (Section **??**).

We measure the VPT response to these light sources. The VPT has three terminals: Anode, Cathode, and Dynode. The Anode and Cathode are read by the ADC. The Cathode signal first goes through two 10x multipliers before going to the ADC. Even after this amplification the Cathode signal strength is less than 10% of the Anode's final signal strength. The Anode's signal is sent through a Stephenson Amplifier before reaching the ADC. In addition to the anode signal, the amplifier admits a test signal, which is sent by the Pulser every measurement cycle.

2.2 Pulser Configuration

A schematic of the pulse generator is included as an appendix.

2.3 File Format

The current file format has fifteen (15) columns. An annoted sample of the file looks like this:

						PIN	Cathode				PIN		AMP	
Time	Type	Pulse	Rate	VPT_1	VPT_2	PIN_{Ref}	Ref_1	Ref_2	LS_1	LS_2	PIN_{Load}	PIN_{Soak}	1	2
3491	1	3	5405	27	27	23	58	69	258	289	90	110	45	51
5498	3	3	5405	869	750	830	116	131	624	919	514	918	705	754
7507	1	3	5405	22	26	23	64	89	264	241	90	110	48	54
9516	3	3	5405	874	748	833	115	116	603	989	514	919	712	758
11525	1	3	5405	29	30	23	52	79	260	254	90	109	51	52
13535	3	3	5405	851	738	830	111	134	617	921	518	921	704	753
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Time index in milliseconds of pulse.

Type $\in \{1, 3\}$:

1 Offset (pedestal) measurement

3 Signal measurement

Pulse $\in \{0, 1, 2, 3\}$: Declares whether the the DAC received the load or soak pulse, or both.

$$0 \rightarrow \text{NONE} \qquad 1 \rightarrow \text{SOAK} \qquad 2 \rightarrow \text{LOAD} \qquad 3 \rightarrow \text{BOTH}$$

Rate Frequency (in hertz) of pulses

VPT1, VPT2 Read out (in ADC counts) of anode current after Stephenson Amplifier

Cathode Ref Read out (in ADC counts) of reference cathode current by the ADC

Cathode LS Read out (in ADC counts) of the load/soak cathode current by the ADC

PIN PIN diode read out (in ADC counts) of the Load, Soak, and Reference LEDs

Amp Read out (in ADC counts) of the amplifier test pulse

3 Experimental Procedure

3.1 Processing

A program was written in Python with SciPy so that rapid changes could be made. As the data was taken, it often became useful to look at it in ways the original program wasn't able to handle. Python made it easy to rewrite core functions rapidly. SciPy affords many of the luxuries which kept Fortran at the forefront of scientific computing for decades, such as whole-array operations on multidimensional arrays with simple syntax and high speed libraries, without explicitly declaring complicated types at every step.[1]

Every 0.4 seconds a measurement is recorded in the data file, alternating signal or offset. So, every 0.8 seconds a complete measurement is taken. We take every signal measurement which is immediately followed by an offset measurement and subtract the offset from the signal to get the measured VPT response.

As is usual, there are small variations in sequential measurements. With over 700 hours of data, or 13 million lines, averaging is warranted. A period of 20 minutes was chosen to reduce the number of data points to a managable level while still preserving a gaussian distribution within the period being averaged.

A curve fitting procedure was written which assumes a negative slope to the data and can guess initial values for a variety of functions. This procedure can subdivide the data into any number of intervals. It can demonstrate, for instance, that the anode does not follow an exponential decay

[1]Python is a strongly, yet dynamically, typed language.

($N = N_0 e^{-\alpha t}$) unless the "decay constant" (α) is considered to be a function which is variable with time. For example, figure 8.

4 Errors

4.1 Data Recording

There's a significant level of noise in the cathode measurements. For the ADC to be able to record the cathode signal, it needs to be amplified one hundred times. Even so, the cathode signal measures around 8 % of the anode signal. So, the same variability in ADC Counts yields a higher percentage variation, in addition to the amplifier noise. Averaged, the cathode signal decays very similarly to the anode signal.

Occationally the CAMAC is unable to take data for a measurement cycle. However, sometimes it enters a failure mode where it is only occationally able to take data. This can last for many minutes. As a result, some time intervals have very few data points. This data turns out to be consistent with the surrounding measurements. It does, however, yield gaps when small periods are averaged, or anomalously large error bars in regions with few data points.

4.2 PIN Shift

Adapted from Diode_Offset.tex

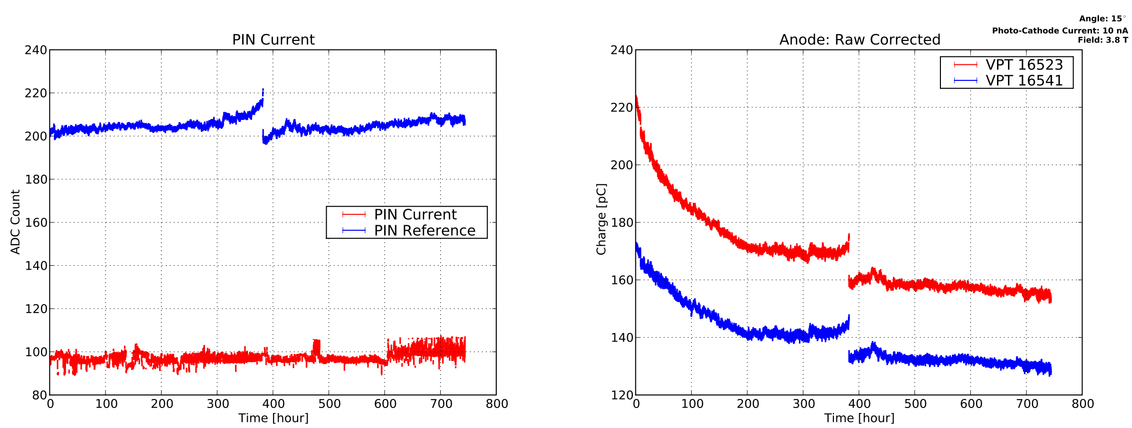


Figure 3: Reference PIN Diode shift at ∼380 hours

Centered near 380 hours into the experiment, the reference LED light rose nearly 10 % and then dropped to just below the original mean. We correct for LED light fluctuation, however this large shift showed up in the corrected data. Each individual measurement was corrected by the PIN diode measurement's fluxuation from its mean. (Note: "Uncorrected" is not a raw measurement, but the signal measurement less the offset measurement.)

$$\text{PIN Corrected Anode} = \text{Uncorrected Anode} + (\text{Averaged Anode})\frac{(\text{Averaged PIN}) - (\text{Measured PIN})}{\text{Averaged PIN}}$$

The PIN Diode measurement used was unmodified. There is likely to be some variation in light admitted to each of the three fibers coming from each LED. In addition, there could be some baseline difference between the PIN Diode measurements and the VPT measurements. Both of these would be solved by introducing an offset to the PIN Diode measurement. This is represented by a new term in the denominator of the correction term. (It subtracts out of the numerator).

If we assume that two points on either side of the shift should be equal, we can solve for the correction term, and plug in measured values for any two such points. These values were calculated to be 105.0625 ± 0.8367 and 62.1866 ± 3.5847 ADC Counts for VPT 1 and VPT 2. We have not yet had the opportunity to test these offsets with other pairs of VPTs, but they successfully compensated for the very large PIN shift.

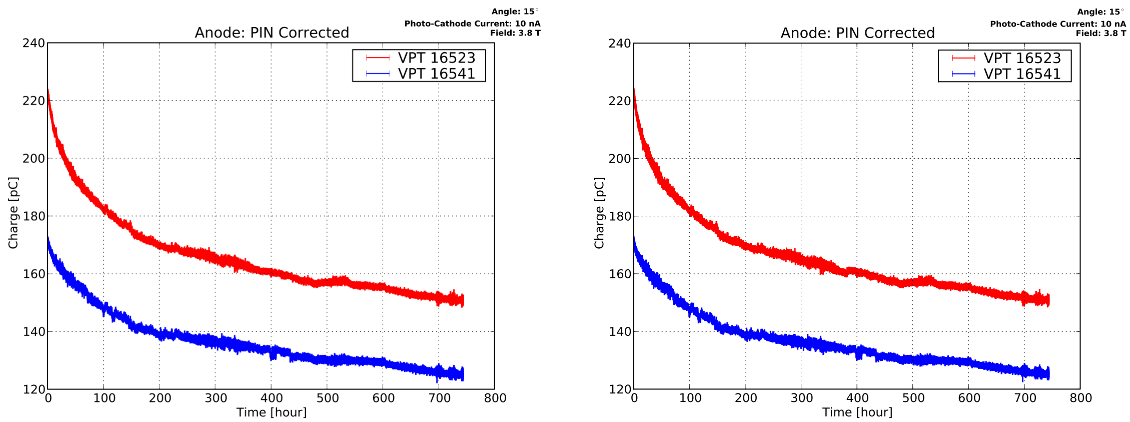


Figure 4: Reference PIN Diode shift at ∼380 hours, Modified Correction (left) and CMS Correction (right)

An alternate solution was proposed in which the correction is:

$$\text{PIN Corrected Anode} = (\text{Uncorrected Anode})\frac{(\text{Averaged PIN})}{(\text{Measured PIN})}$$

This correction substantially reduced the shift, but did not entirely eliminate it. CMS uses this formula to monitor VPT response over time. The persistence of the anode shift under this formula may reflect a real non-linear response in the VPT to the light level shift. While perhaps more correct, the effect of the shift is transitory and does not visibly affect the long-term behavior of the anode signal. As the long-term behavior is under study, it is more important to remove the anomoly entirely if it does not corrupt the data.

5 Data

The Anode and Cathode signal (Figure 6 are corrected for variation of the PIN diode (variation of LED light intensity) and amplifier measurement (Figure 5). The modified correction detailed in *Errors: PIN Shift* (Section 4.2) is used here. In Figure 7 the anode signal is corrected by the corrected photocathode signal. The correction term is the product of the mean signal and the percentage difference of the corrector (PIN, amp, or photo-cathode). So, when we average the intervals over 20 minutes, we see a standard deviation which is proprotional to the error of the corrector.

5.1 Fitting the Data

Initially, the PIN-corrected anode appears to follow an exponential. A fit (Figure 8) quickly dispells this notion, however it does suggest a composition of at least two elementary functions. Working on

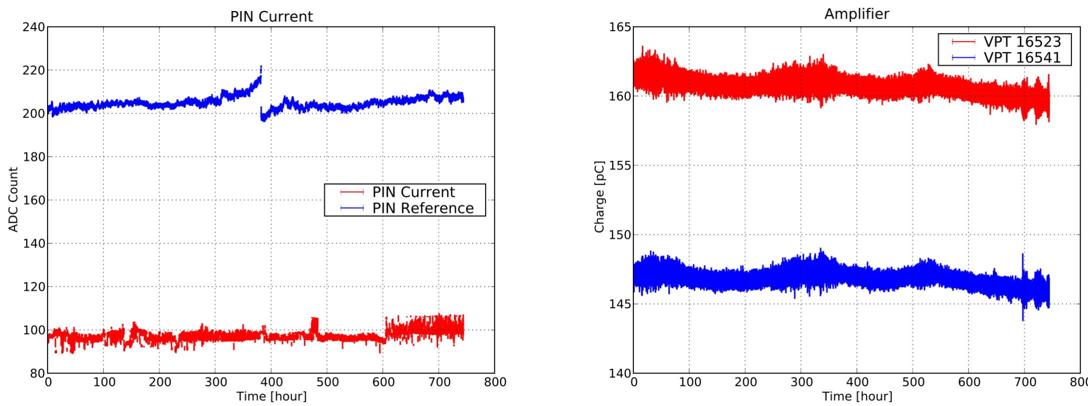


Figure 5: LED and Amplifier stability

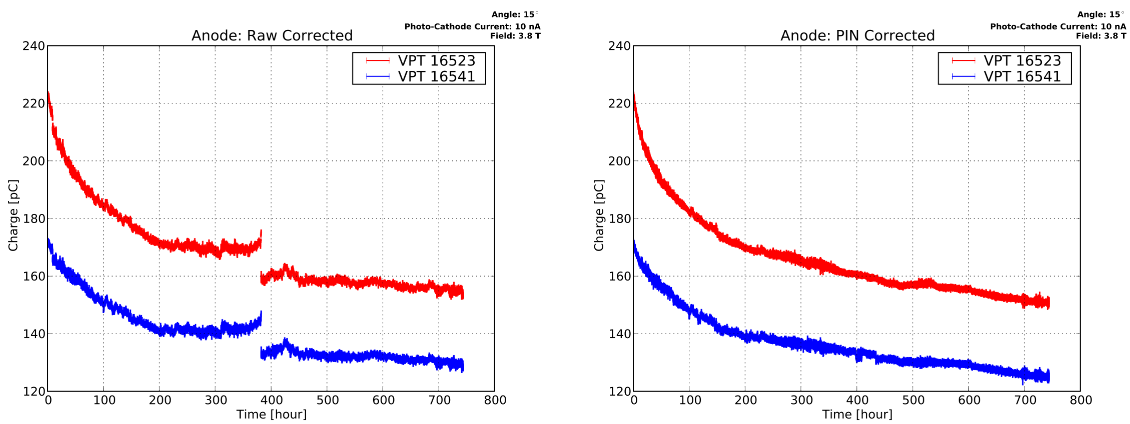


Figure 6: Anode: Raw (left) and PIN Corrected (right)

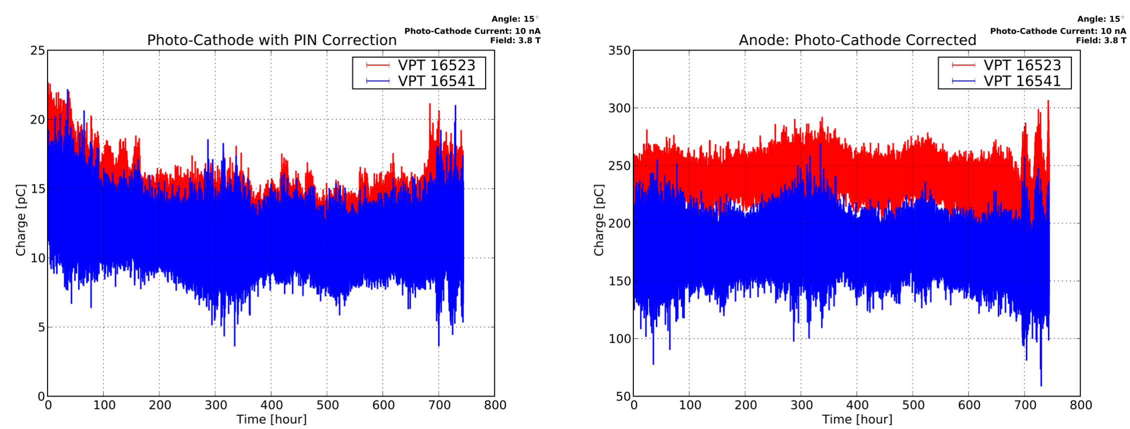
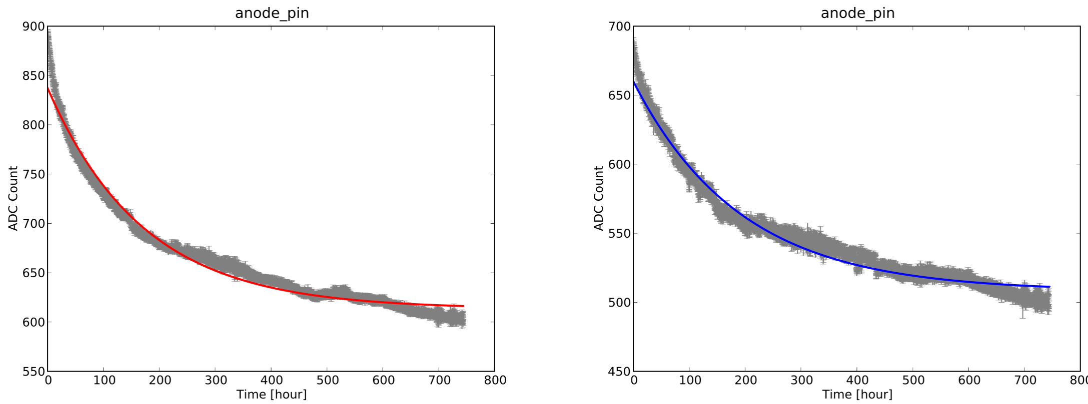
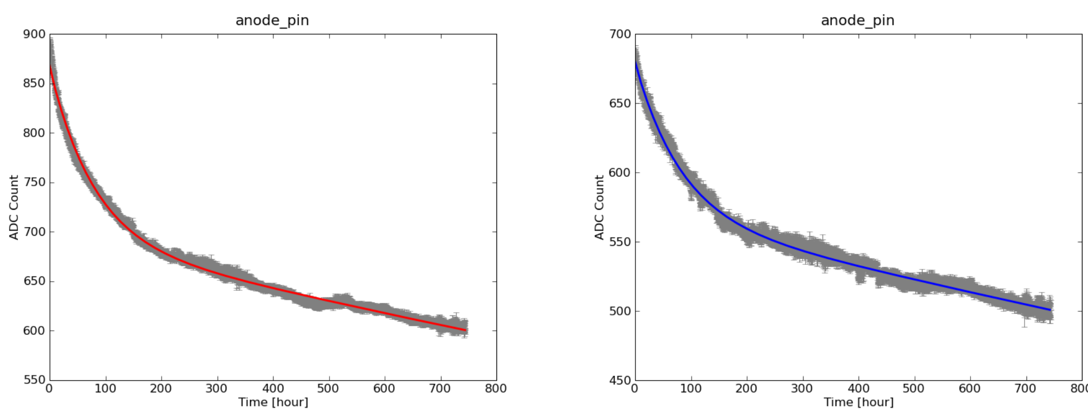


Figure 7: Photocathode and Anode with Photocathode Correction



VPT #	A	α	C	χ^2
16523	224.0	5.836×10^{-3}	613.3	7.85
16541	151.9	5.211×10^{-3}	508.1	3.87

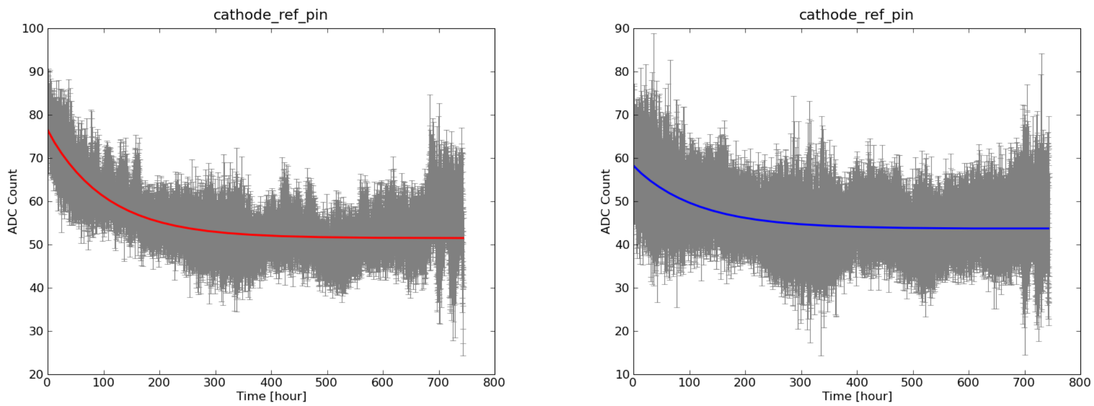
Figure 8: Exponential Fit for VPTs 16523 and 16541



VPT #	A	α	B	β	C	χ^2
16523	$1.677\times10^{+2}$	1.877×10^{-3}	$1.443\times10^{+2}$	1.760×10^{-2}	$5.631\times10^{+2}$	1.245
16541	$4.307\times10^{+3}$	2.115×10^{-5}	$1.120\times10^{+2}$	1.220×10^{-2}	$-3.739\times10^{+3}$	0.967

Figure 9: $Ae^{-\alpha x} + Be^{-\beta x} + C$ Fit for VPTs 16523 and 16541

the assumption that there's a short-term exponential "burn-in" followed by a long-term exponential decay we can make a fit with χ^2 closer to unity. Unfortunately, experimenting with the fits reveals numerous fits with the same χ^2 and vastly different parameters. One possible fit is shown in figure 9. A single exponential term fails to fit the later data without another function, with χ^2 on the order of 7.85 and 3.87.



VPT #	A	α	C	χ^2
16523	$2.50\times10^{+1}$	9.46×10^{-3}	$5.15\times10^{+1}$	0.3831
16541	$1.45\times10^{+1}$	8.79×10^{-3}	$4.37\times10^{+1}$	0.2464

Figure 10: Photocathode Exponential Fit

However, if the Anode is corrected for variation in the photocathode (Figure 7), it appears essentially level. The photocathode appears to follow the exponential quite well (Figure 10), except for the latter region around 700 hours where the the amplifier begins to look odd. (Figure 5) When the pin and amplifier corrected anode is also corrected for photocathode variation it appears essentially flat over 700 hours. The error bars carry the variability of the photocathode, so it's hard to make solid claims about its behavior. In figure 11 an exponential fit is shown for curiousity's sake.

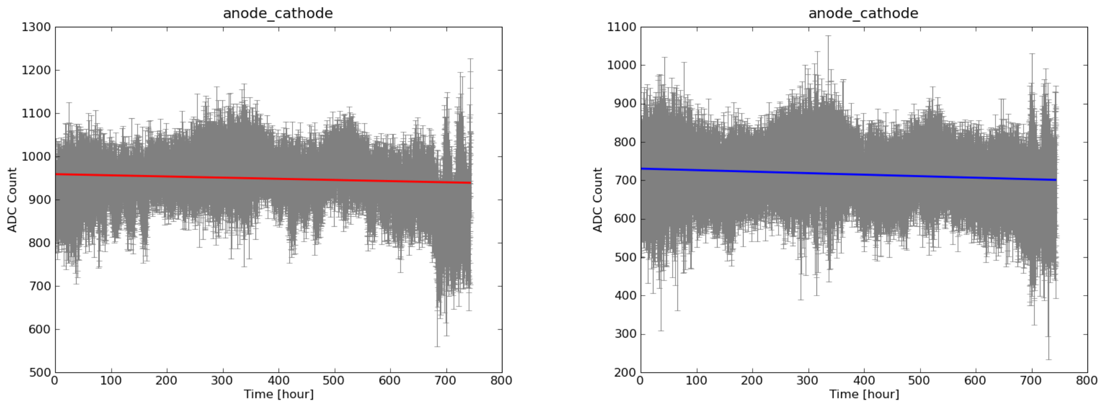
We can try to get a clearer look by correcting the anode with the fitted cathode function (figure 12). However, if one compares figures 10 and 12 they can see that the fit deviates as the corrected plot seems to decay.

If we instead look at the ratio of the uncorrected anode and photo-cathode, the ratio appears flat, even during the burn-in phase. A double-exponential shows a flattening.

6 Conclusions

The anode seems to be composed of a superposition of a short-term burn-in with a long term decline. Despite the decrease in anode and photo-cathode current, the ratio between the two remains relatively constant. The amplification noise in the photo-cathode signal currently precludes a quantitative conclusion about the behavior of the amplification of the photo-cathode signal over time. Qualitatively, from figures 13 and 14, it appears unlikely that there will be significant decline in the ratio of the anode to the photocathode. Were it to follow an exponential or power law, it could not decay significantly further. Even a linear decay would not admit a significant decline.

An equipment failure precluded the completion of this experiment, which would have included a study of the self-correcting behavior. The problem that occured could account for the fitting



VPT #	A	α	C	χ^2
16523	$2.91\times10^{+5}$	9.25×10^{-8}	$-2.90\times10^{+5}$	0.4732
16541	$1.57\times10^{+5}$	2.52×10^{-7}	$-1.56\times10^{+5}$	0.2661

Figure 11: Anode, Photocathode corrected Exponential Fit

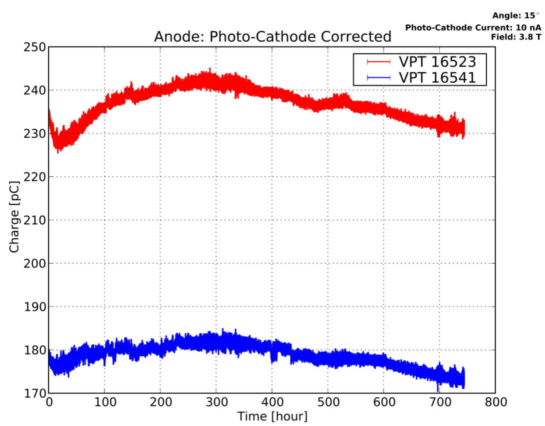


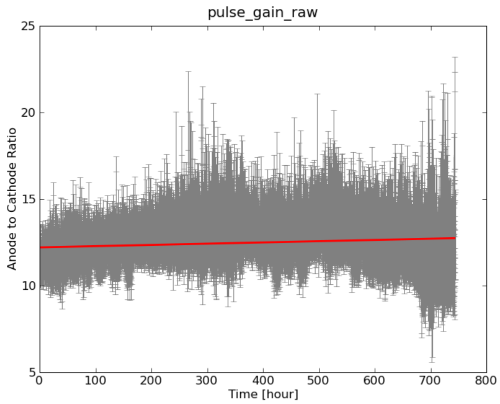
Figure 12: Anode, corrected by Photocathode fitted function

difficulty, as we were able to show signal crossovers in the data that should not have been possible. These processes would have been amplified by the correction algorithm, causing the systematic deviation seen while attempting to fit the data.

6.1 Further Study

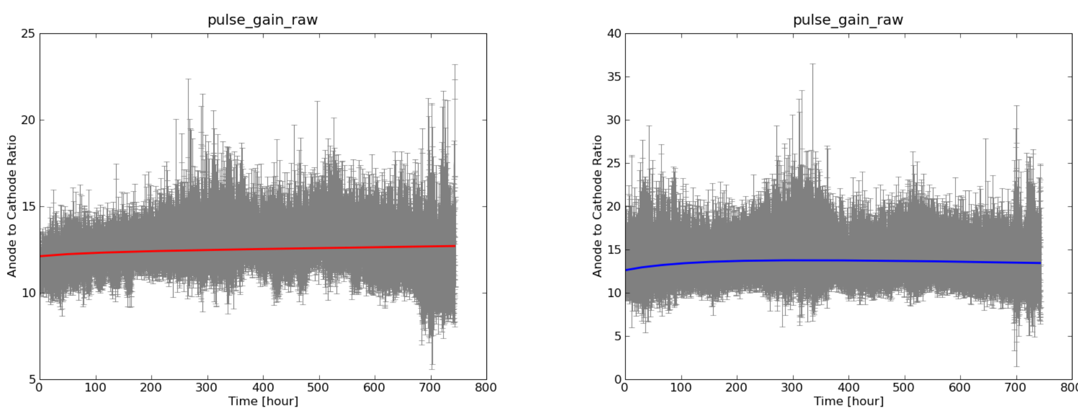
Prior to this experiment, we've seen VPT reponse will restore to prior levels when the apparatus is turned off but the VPTs are left in the magnetic field. A further study will test if the response restoration occurs in the absence of light or power, and describe the behavior of the response decay after the interruption.

In addition, the results of this study should be reproduced with new the equipment from National Instruments purchased in 2009.



VPT #	A	α	C	χ^2
16523	$4.45\times10^{+3}$	-1.61×10^{-7}	$-4.43\times10^{+3}$	0.4203
16541	$2.72\times10^{+3}$	-1.93×10^{-7}	$-2.71\times10^{+3}$	0.2691

Figure 13: Raw Anode/Photo-Cathode Ratio with exponential fit



VPT #	A	α	B	β	C	χ^2
16523	-1.941×10^{-1}	9.932×10^{-3}	$2.283\times10^{+3}$	-2.279×10^{-7}	$-2.270\times10^{+3}$	0.4054
16541	-1.553	7.798×10^{-3}	$-6.590\times10^{+3}$	-1.499×10^{-7}	$6.604\times10^{+3}$	0.2531

Figure 14: Raw Anode/Photo-Cathode Ratio with double-exponential fit

Pulser Documentation

Slot	Title	Make/Model
1	Quad Gate/Delay Generator #1	PS 794
2	Logic Fan-In/Fan-Out	LeCroy 429A
3	none	none
4	Quad Gate/Delay Generator #2	PS 794
5	Quad Gate/Delay Generator #3	PS 794
6	Quad Linear Fan-In/Fan-Out	PS 740
7	Quad Four-Fold Logic Unit	PS 755
8	Octal Logic Unit	PS 758
9	Frequency Divider	(unavail.)
10	Level Translator	PS 726
11	Linear Fan-In/Out	FS 7139
12	none	none

Table 1: Contents of PS 700 Crate

Slot	Sub	In Use	Setting
1	1	no	1 ms
1	2	no	10 µs
1	3	yes	1 µs
1	4	yes	10 s
2	all	yes	center
4	1	yes	1 ms
4	2	yes	1 µs
4	3	yes	1 ms
4	4	yes	1 µs
5	1	no	1 ms
5	2	yes	1 ms
5	3	yes	1 µs
5	4	yes	1 ms
6	—	—	n/a
7	all	yes	coincidence level 4
8		yes	AND; veto empty
9	all	yes	1

Table 2: Settings for Crate Modules

Pulse LEMO Schematic