PMT Non-Linearity Studies at ISU

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Outline

- Introduction and Motivation
- Linearity Test Apparatus
- Light Level Selection
- Measurement and Analysis Techniques
- Results and Summary

Introduction (What is Asymmetry? What is non-linearity)?

LED

$$A_{LED} = \frac{N^+ - N^-}{N^+ + N^-} \qquad \text{With, } N_{avg} = \frac{N^+ + N^-}{2}$$

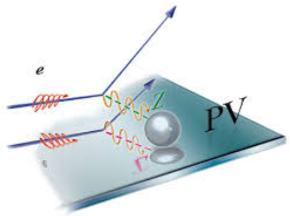
$A_{LED} = A_{true}(1 + \beta N_{avg})$ is the fit function.

- $N^{\pm} = N_S^{\pm}(1+\beta N_S^{\pm})$ is the PMT response for the signal $N_S^{\pm}$.
- β parameterizes the non-linearity
- N_{avg} settings provided by ND filter wheel
- Fits to A_{LED} vs. N_{avg} plot give A_{true} and $A_{true}\beta$ and hence the non-linearity.

- Linearity measurement plays an important role in detector systematics.
- R7723Q PMT with modified base for improved non-linearity was used.

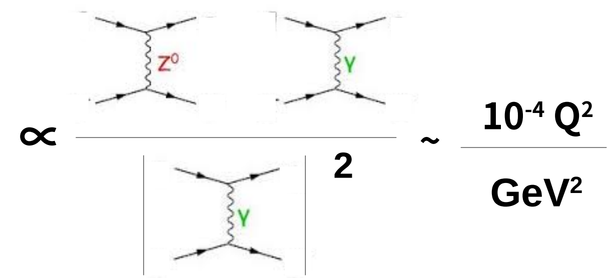
PREx-II/CREx

- Polarized beam with unpolarized target.
- Measurements in opposite helicity states.
- Asymmetry of cross sections:

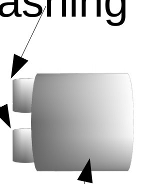


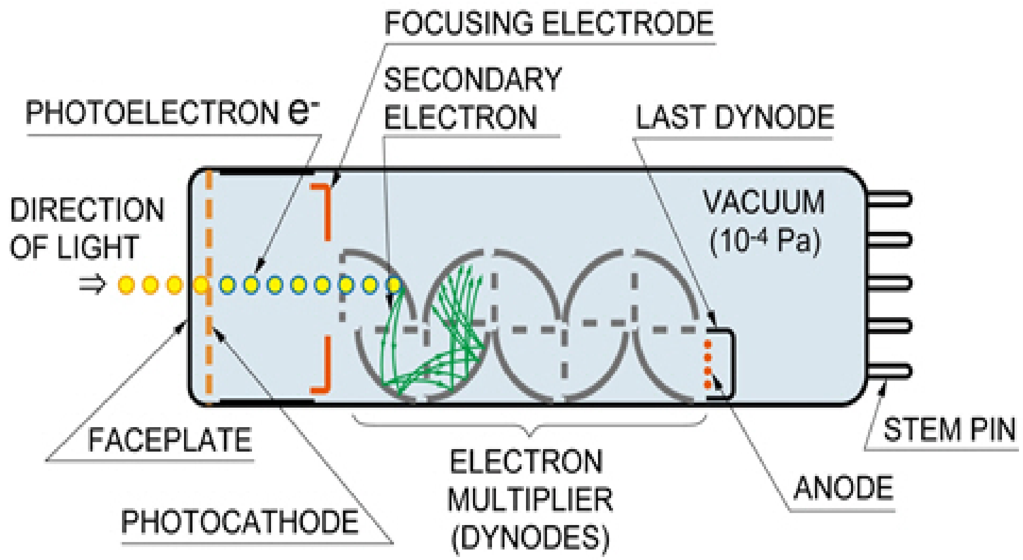
$$A_{pv} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$$\sigma_{R(L)} = \frac{d\sigma_{R(L)}}{d\Omega} \propto (S_\gamma + S_Z^{R(L)})^2$$



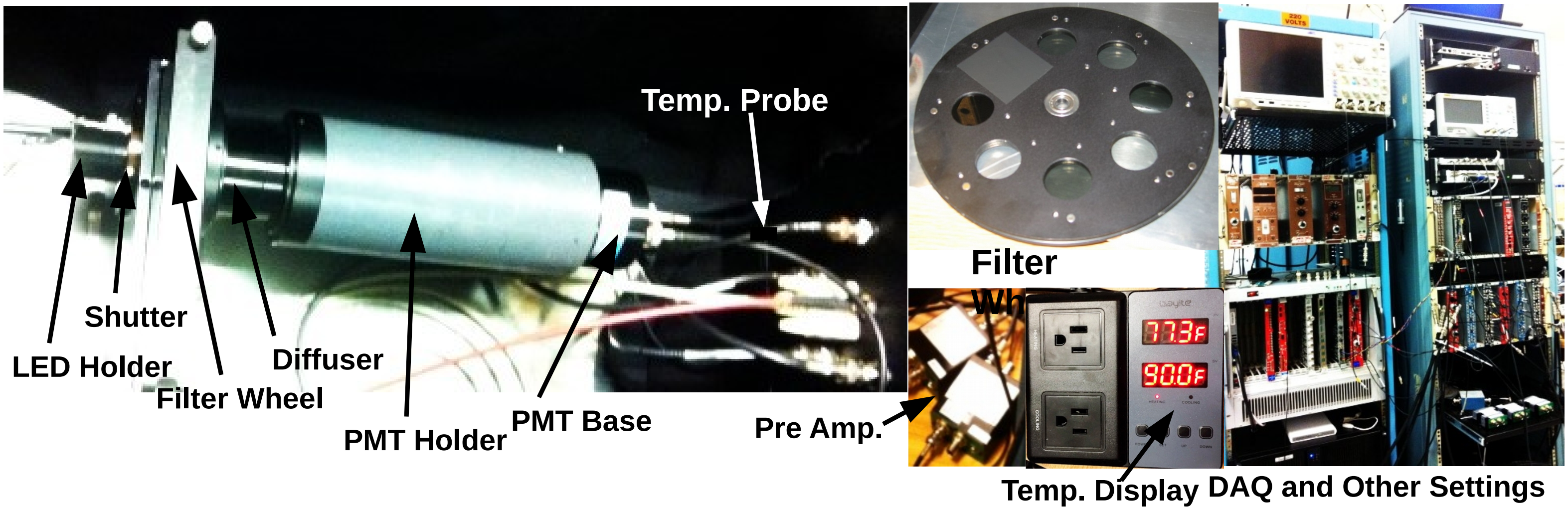
Why Linearity Study is Important for PREx-II/CREx?





- PMTs tested here will be used in the PREx-II/CREx detectors
- PMT non-linearity is an important systematic error and needs to be understood well before experiment
- The systematic error budget for detector non-linearity is 0.3 % (CREx) and 1 % (PREx-II)

Linearity Test Box And Integrating DAQ



- LED Holder → holds two LEDs, each with 2 mm diameter collimation
- Electronic Shutter → has now been connected with a relay to turn it “ON” and “OFF” automatically at any interval with computer script
- Filter Wheel → Computer Controlled Edmund Optics’ Absorptive ND filters (400-700 nm) with 8 (100, 79, 63, 50, 40, 25, 10, 1)% transmission settings (~randomly ordered)
- Filter Wheel is now controlled automatically using a shell script
- UV Diffuser → Edmund Optics’ ground fused silica
- PMT Holder → 2” PMT with modified base for improved linearity
- Different pre-Amp settings with different resistances and offsets tested (MAIN, LUMI, KDPA, and SNS)

Maintaining Temperature Stability of Apparatus During Measurements

➔ Temperature probe has been installed inside the linearity test box in order to monitor the air temperature near PMT base.

➔ We now turn on HV at least 24 hrs before taking data – helps stabilize PMT temperature (with smaller fluctuation during data taking).

➔ After changing HV, we now wait at least 15-20 minutes before starting next run (helps in temperature stabilization).

Apparatus Improvements

- Now the LED, Trigger, and Gate timings have been controlled through HAPPEX Timer board.
- Light level (LL) has now been calibrated using DAC16, which improves the resolution in LL selection.
- Need to calibrate picoammeter used for LL measurement.
- Need to get unity gain base for R7723Q.

Qweak ADC Details

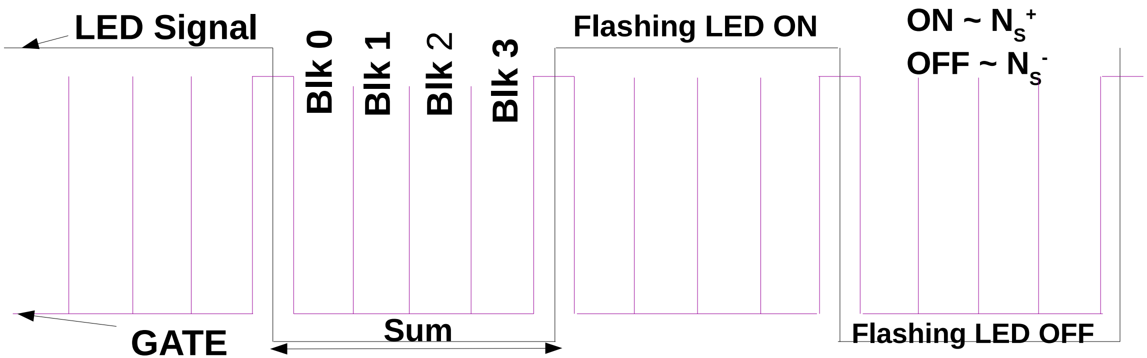


Figure: DAQ response sampled in four blocks.

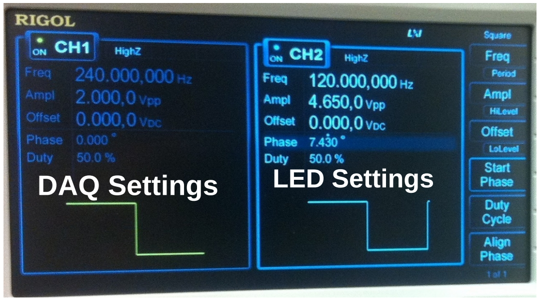


Figure: Function Generator settings.

- Samples the voltage every 2 μs
- Has a ±10 V range with 18 bit resolution (corresponding to 76.29 μV/channel)
- Has 8 inputs with 12 Ω input impedance
- Working with CODA 2.6.2 and a Linux ROC
- We use a Struck SIS3610 for triggering
- Each GATE is split into 4 blocks with the length (in time) of each block specified by user
- For 120 Hz flipping rate, we set 500 samples/block. So 2000 total samples, every 2 μs, gives 8000 μs long gate
- We are currently using a function generator to provide synchronized DAQ and LED driver signals

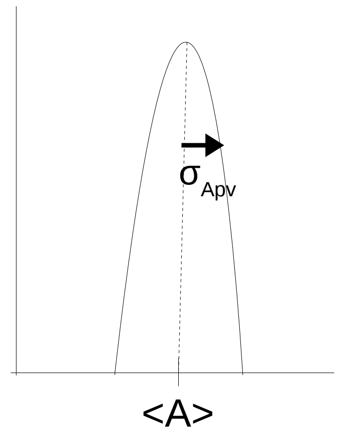
Light Level $\Longleftrightarrow I_{cathode}$

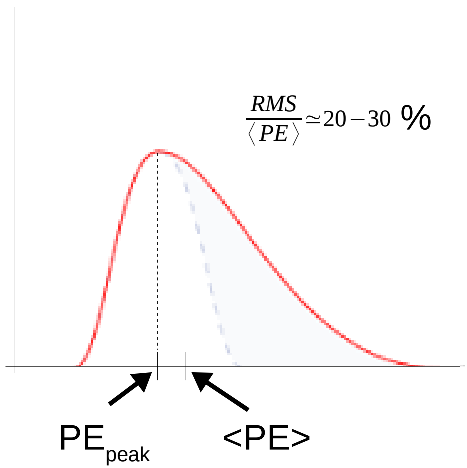
- Used constant LED
- Used unity gain PMT (R375)
- Used DAC 16 for constant LED
- Used pico-ammeter to measure I_c which is effectively I_{PE} because gain is 1
- QE of R375 PMT is different but similar to R7723Q PMT. Planning to get unity gain base for R7723Q PMT
- PMTs should show the best linear response with the LL equivalent to Cerenkov light that it receives during PREx-II/CREx

Light Level Validation During Commissioning

- Set HVs to our expected best values
- Collect “production” data
- Infer LL from measured Asymmetry width (σ_{Apv}):

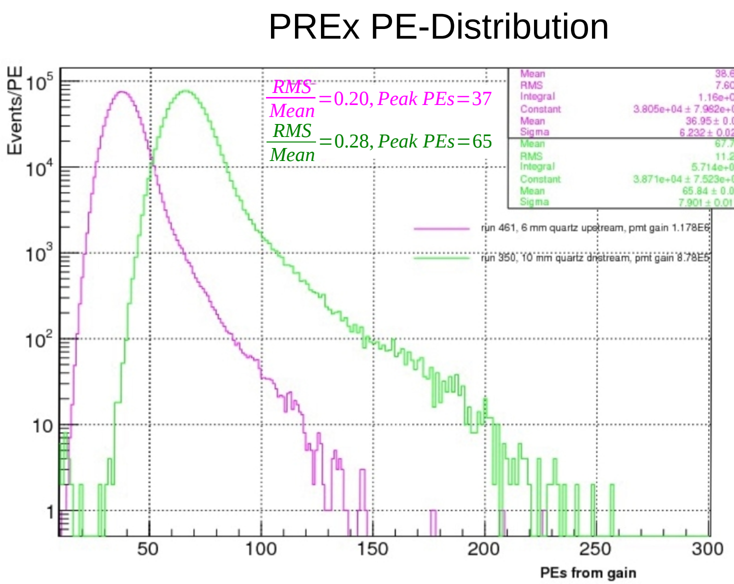
$$rate = \frac{fliprate}{2(\sigma_{Apv})^2}\left[1 + \left(\underbrace{\frac{RMS}{\langle PE \rangle}}_{\text{Excess Noise}}\right)^2\right]$$





- LL ≡ I_c = rate x PE_{peak} x 1.602 x 10^{-19}
- Can also check for consistency between up-and down-stream widths for each arm separately and between the two arms.

Selection of Light Levels to Test



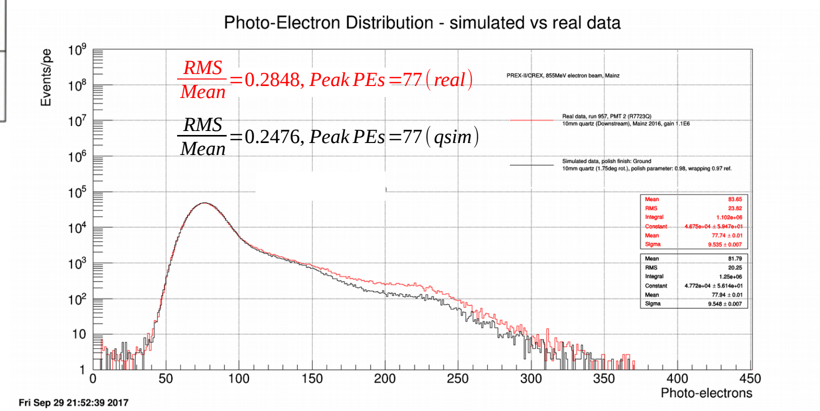


Figure: Produced by Carlos Bula

PREx-II	CREx
• Rate = 1 GHz • LL for upstream quartz = 1GHz*37*e ~ 6 nA • LL for downstream quartz ~ 10 nA (65 peak PEs)	• Rate = 50 MHz • LL for upstream quartz = 50MHz*37*e ~ 0.3 nA • LL for downstream quartz ~ 0.5 nA (65 peak PEs)

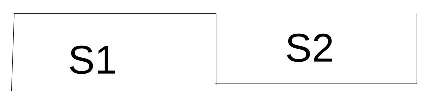
→ Tested 3 PMTs so far

Steps in Data Collection

- LL controlled by HAPPEx timer DAC16, calibrated using R375 PMT with unity gain base
- DAQ (240 Hz) and LED flash (120 Hz) signals were synchronized
- Proper timing setting between LED, TRIGGER and GATE (45 μs and 100 μs respectively) was maintained (GATE duration is 8000 μs and the GATE does not start until 20 μs after the ADC receives the GATE signal)
- An automated filter wheel and shutter script orchestrated the data collection over 20 cycles of filter wheel:
  - Each filter stayed in its position for 10 sec and during each filter change the shutter remains closed for 2 sec
  - Just before each new filter cycle, pedestal data was taken for 5sec
  - Asymmetry Mean and Error from 20 cycles of filter wheel was used to produce non-linearity plot (A_{LED} vs N_{avg})

Steps and Approaches in Data Analysis

- Used simplified version of vQwk Analyzer to analyze data
- An automated c++ code has been developed that removes any “unclean” data during filter rotation and analyzes the rest
- The data from two consecutive gates were used to calculate simple pair-wise asymmetry

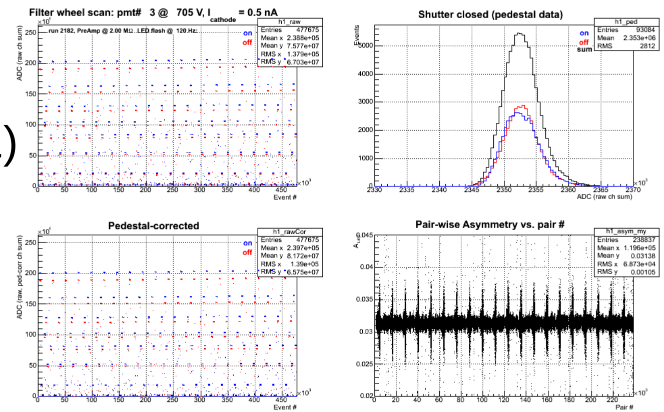


$$A = \frac{S_1 - S_2}{S_1 + S_2}$$

Measurement Steps

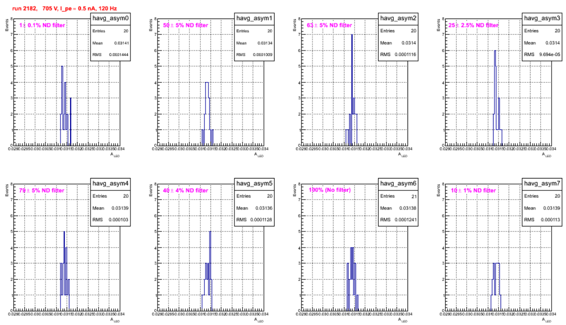
- Take data with 120 Hz of flipping rate for 20 cycles of filter wheel rotation.
- Subtract pedestal, and find pairwise asymmetry.

(1)



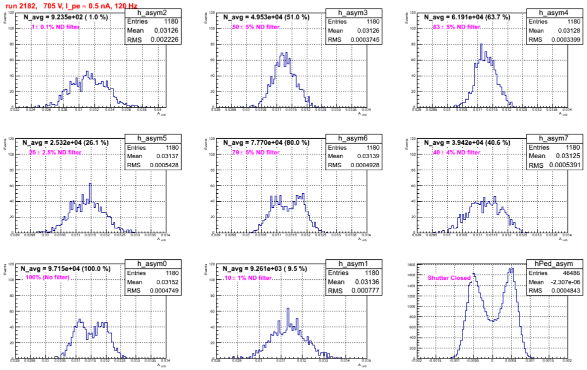
- Plot the mean asymmetry for each filter cycle.
- Find the mean and RMS for all 20 cycles.

(3)



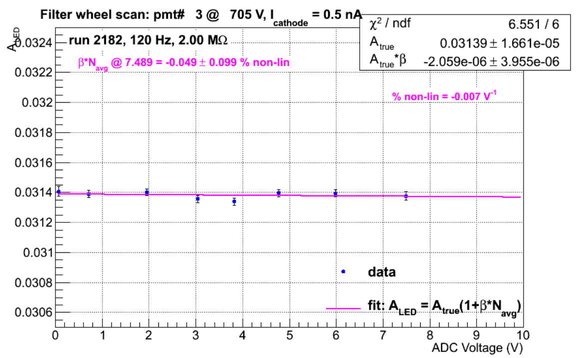
- Plot asymmetry for individual filter setting.
- Find the mean of each plots.

(2)

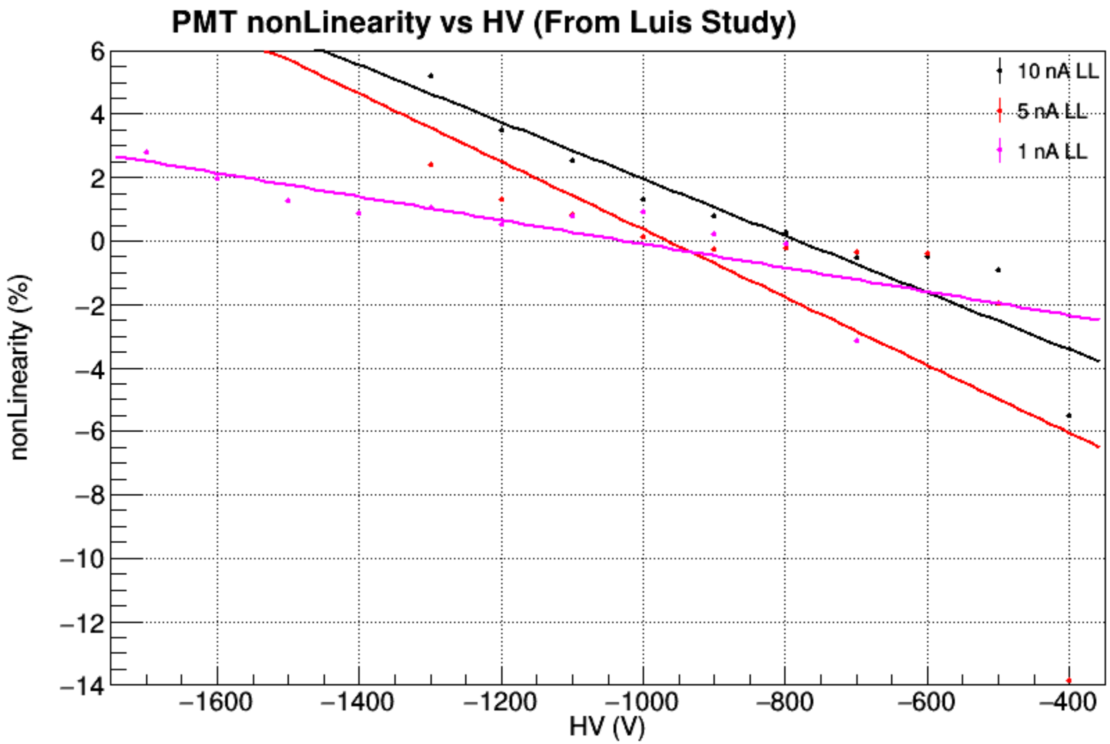


- Plot the mean asymmetry vs ADC Voltage for each filter setting.
- Linear fit the data points calculate slope and hence non-linearity

(4)



Linearity Study in the Past



LL = 10 nA

HV	I_{out}	nonLin
-400	0.54	-5.5
-500	1.56	-0.9
-600	3.7	-0.48
-700	7.8	-0.54
-800	15	0.28
-900	26	0.78
-1000	43	1.32
-1100	68	2.52
-1200	104	3.48
-1300	155	5.2

LL = 5 nA

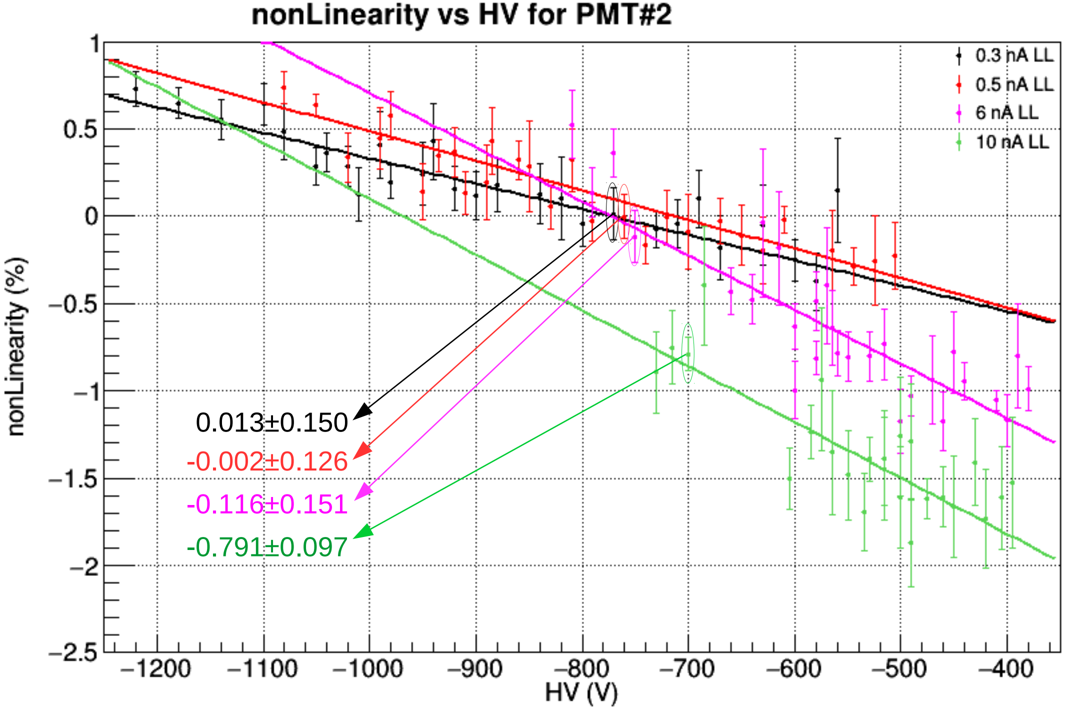
HV	I_{out}	nonLin
-400	0.26	-13.85
-500	0.76	-1.96
-600	1.8	-0.39
-700	3.8	-0.34
-800	7.2	-0.21
-900	12.6	-0.26
-1000	20.7	0.11
-1100	32.4	0.82
-1200	48.5	1.29
-1300	70	2.41

LL = 1 nA

HV	I_{out}	nonLin
-700	0.75	-3.15
-800	1.4	-0.075
-900	2.5	0.23
-1000	4.1	0.93
-1100	6.3	0.79
-1200	9.4	0.51
-1300	13.5	1.03
-1400	18.8	0.88
-1500	26.3	1.27
-1600	34	1.98
-1700	44	2.79

Figure: Reproduced From Luis Mercado's Dissertation.

Summary for PMT#2



LL = 0.3 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
1938	-1220	0.3	0.729	0.100	4.872
1939	-1180	0.3	0.648	0.089	2.709
1940	-1140	0.3	0.552	0.113	5.997
1941	-1100	0.3	0.645	0.119	7.070
1947	-1080	0.5	0.483	0.161	8.400
1948	-1050	0.5	0.287	0.106	3.625
1949	-1020	0.5	0.286	0.113	9.049
1950	-990	0.5	0.409	0.193	12.29
1933	-1040	0.6	0.366	0.114	4.405
1934	-1010	0.6	0.129	0.153	12.35
1935	-980	0.6	0.197	0.096	2.246
1936	-950	0.6	0.243	0.179	13.31
1952	-940	1.0	0.430	0.218	18.58
1953	-920	1.0	0.160	0.127	7.389
1954	-900	1.0	0.119	0.140	8.746
1955	-880	1.0	0.180	0.150	5.322
1957	-840	2.0	0.129	0.170	8.034
1958	-820	2.0	0.106	0.237	10.61
1959	-800	2.0	-0.042	0.132	4.793
1960	-770	2.0	0.013	0.150	7.264
1961	-730	4.0	-0.075	0.104	3.345
1962	-710	4.0	-0.042	0.136	4.074
1963	-690	4.0	0.099	0.166	5.990
1964	-670	4.0	-0.180	0.180	3.660
1943	-630	10.0	-0.050	0.230	10.84
1944	-600	10.0	-0.252	0.116	1.585
1945	-580	10.0	-0.374	0.162	3.719
1946	-560	10.0	0.148	0.299	10.35

LL = 6.0 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
2073	-810	0.1	0.526	0.194	26.24
2074	-790	0.1	0.137	0.138	16.51
2075	-770	0.1	0.360	0.138	4.003
2076	-750	0.1	-0.116	0.151	10.63
2050	-660	0.3	-0.429	0.135	6.789
2046	-640	0.3	-0.475	0.140	15.70
2047	-630	0.3	-0.037	0.424	85.80
2048	-615	0.3	-0.182	0.326	41.56
2056	-600	0.5	-0.996	0.163	12.75
2057	-580	0.5	-0.488	0.170	11.90
2058	-570	0.5	-0.398	0.334	65.96
2059	-560	0.5	-0.787	0.131	9.769
2052	-600	0.6	-0.631	0.133	11.49
2053	-580	0.6	-0.814	0.096	6.912
2054	-565	0.6	-0.640	0.215	26.28
2055	-550	0.6	-0.805	0.141	7.201
2060	-530	1.0	-0.803	0.144	19.21
2061	-515	1.0	-0.733	0.201	33.30
2062	-500	1.0	-1.174	0.182	12.41
2063	-490	1.0	-1.027	0.114	4.954
2064	-470	2.0	-0.938	0.253	28.87
2065	-460	2.0	-1.176	0.169	22.99
2066	-450	2.0	-0.780	0.234	24.39
2067	-440	2.0	-0.944	0.108	7.177
2068	-410	4.0	-1.054	0.057	1.070
2070	-400	4.0	-1.169	0.150	9.485
2071	-390	4.0	-0.800	0.297	36.38
2072	-380	4.0	-0.990	0.127	7.438

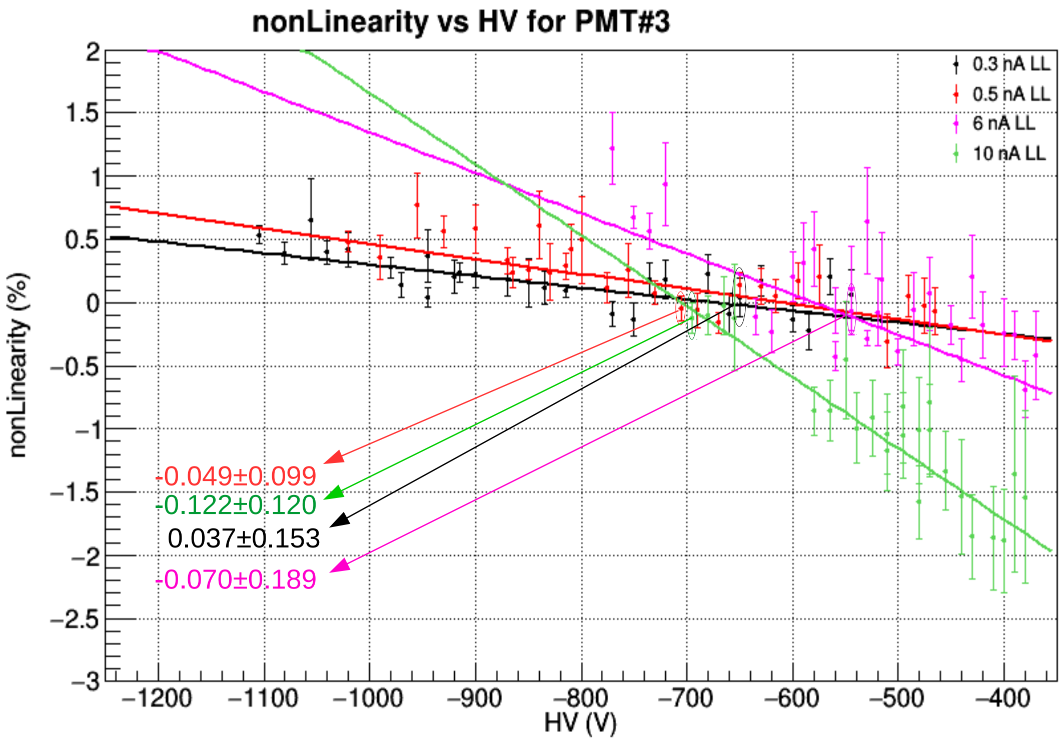
LL = 0.5 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
1991	-1080	0.3	0.739	0.093	1.902
1992	-1050	0.3	0.638	0.058	1.598
1993	-1020	0.3	0.337	0.139	9.607
1994	-990	0.3	0.445	0.177	9.531
1982	-980	0.5	0.574	0.137	6.722
1983	-950	0.5	0.141	0.159	14.17
1984	-920	0.5	0.369	0.143	7.609
1986	-890	0.5	0.196	0.216	12.08
1995	-935	0.6	0.345	0.091	4.216
1996	-910	0.6	0.132	0.123	8.034
1997	-885	0.6	0.432	0.194	19.43
1998	-860	0.6	0.321	0.110	8.270
1987	-850	1.0	0.284	0.260	27.48
1988	-830	1.0	0.054	0.125	5.673
1989	-810	1.0	0.322	0.180	12.91
1990	-790	1.0	-0.031	0.113	6.962
1972	-760	2.0	-0.002	0.126	5.791
1973	-740	2.0	-0.165	0.110	2.221
1974	-720	2.0	-0.008	0.157	6.458
1975	-700	2.0	-0.092	0.214	20.77
1967	-670	4.0	-0.026	0.132	3.998
1968	-650	4.0	-0.108	0.172	8.149
1969	-630	4.0	-0.197	0.189	5.280
1970	-610	4.0	-0.019	0.076	1.627
1976	-565	10.0	-0.195	0.232	16.88
1978	-545	10.0	-0.286	0.106	2.188
1979	-525	10.0	-0.253	0.254	10.81
1980	-505	10.0	-0.224	0.190	4.669

LL = 10.0 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
2102	-730	0.1	-0.893	0.233	17.05
2103	-715	0.1	-0.750	0.212	18.20
2104	-700	0.1	-0.791	0.095	4.500
2105	-685	0.1	-0.398	0.341	70.38
2098	-605	0.3	-1.504	0.178	11.27
2099	-585	0.3	-1.236	0.154	13.39
2100	-575	0.3	-0.934	0.408	102.2
2101	-565	0.3	-1.354	0.357	49.27
2088	-550	0.5	-1.484	0.256	42.98
2089	-535	0.5	-1.694	0.224	32.93
2090	-515	0.5	-1.448	0.296	46.25
2091	-500	0.5	-1.260	0.339	24.36
2093	-530	0.6	-1.391	0.128	9.687
2094	-515	0.6	-1.386	0.272	41.63
2096	-500	0.6	-1.611	0.290	50.45
2097	-490	0.6	-1.874	0.252	34.81
2083	-490	1.0	-1.288	0.329	71.75
2084	-475	1.0	-1.618	0.117	8.316
2085	-460	1.0	-1.609	0.171	18.30
2086	-450	1.0	-1.666	0.292	38.59
2079	-430	2.0	-1.409	0.246	36.01
2080	-420	2.0	-1.731	0.284	31.41
2081	-405	2.0	-1.613	0.293	79.77
2082	-395	2.0	-1.529	0.375	67.14

Summary for PMT#3



LL = 0.3 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
2242	-1105	0.3	0.538	0.070	2.229
2245	-1080	0.3	0.392	0.085	2.630
2244	-1055	0.3	0.655	0.323	78.83
4246	-1040	0.3	0.396	0.089	3.307
2232	-1020	0.5	0.418	0.132	6.555
2233	-980	0.5	0.277	0.084	3.254
2236	-945	0.5	0.366	0.206	21.98
2235	-915	0.5	0.239	0.073	3.526
2237	-970	0.6	0.144	0.099	4.944
2238	-945	0.6	0.041	0.073	4.265
2239	-920	0.6	0.205	0.134	9.197
2240	-900	0.6	0.231	0.119	2.264
2228	-870	1.0	0.181	0.133	8.208
2229	-850	1.0	0.157	0.191	12.07
2230	-835	1.0	0.114	0.133	11.41
2231	-815	1.0	0.093	0.047	0.778
2209	-770	2.0	-0.094	0.098	5.369
2211	-750	2.0	-0.132	0.132	11.97
2212	-735	2.0	0.182	0.132	6.689
2215	-720	2.0	0.187	0.152	16.48
2217	-680	4.0	0.226	0.151	11.18
2218	-660	4.0	-0.089	0.165	14.11
2219	-650	4.0	0.037	0.153	8.451
2220	-630	4.0	0.171	0.121	6.446
2222	-600	10.0	-0.130	0.104	4.948
2226	-585	10.0	-0.219	0.155	8.466
2224	-565	10.0	0.206	0.138	12.54
2245	-545	10.0	0.064	0.190	20.87

LL = 6.0 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
2154	-770	0.1	1.221	0.282	29.33
2155	-750	0.1	0.672	0.086	4.787
2157	-735	0.1	0.564	0.140	4.744
2158	-720	0.1	0.936	0.331	63.63
2144	-635	0.3	-0.115	0.140	6.057
2177	-620	0.3	-0.230	0.170	10.59
2147	-600	0.3	0.205	0.195	19.37
2148	-590	0.3	0.318	0.317	56.22
2163	-580	0.5	0.419	0.296	42.13
2164	-560	0.5	-0.426	0.116	8.968
2165	-545	0.5	0.110	0.334	23.33
2166	-530	0.5	0.645	0.418	42.82
2149	-560	0.6	-0.063	0.184	23.28
2150	-545	0.6	-0.070	0.189	7.863
2151	-530	0.6	-0.285	0.060	2.140
2153	-520	0.6	-0.076	0.266	62.65
2159	-515	1.0	0.181	0.377	103.7
2160	-500	1.0	-0.389	0.104	2.674
2161	-485	1.0	-0.053	0.291	55.89
2262	-470	1.0	0.069	0.289	29.13
2173	-450	2.0	-0.178	0.150	6.963
2174	-440	2.0	-0.456	0.169	14.82
2175	-430	2.0	0.205	0.323	49.27
2176	-420	2.0	-0.175	0.260	47.61
2167	-400	4.0	-0.240	0.265	21.39
2168	-390	4.0	-0.258	0.189	23.87
2169	-380	4.0	-0.686	0.225	16.90
2171	-370	4.0	-0.417	0.348	41.25

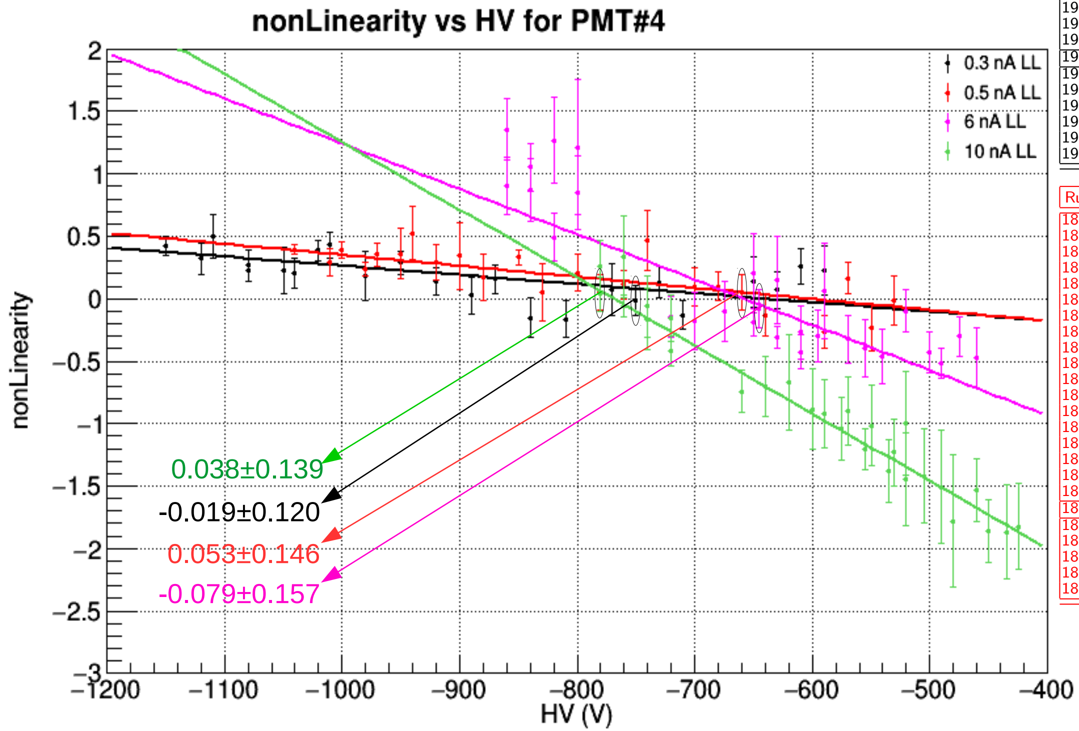
LL = 0.5 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
2199	-1020	0.3	0.481	0.084	1.706
2200	-990	0.3	0.360	0.173	14.46
2201	-955	0.3	0.768	0.260	24.63
2203	-930	0.3	0.562	0.124	11.19
2191	-900	0.5	0.585	0.192	19.69
2192	-865	0.5	0.234	0.121	5.292
2193	-840	0.5	0.614	0.263	38.23
2194	-815	0.5	0.287	0.104	8.041
2195	-870	0.6	0.331	0.104	5.364
2196	-850	0.6	0.261	0.080	2.051
2197	-830	0.6	0.243	0.228	30.84
2198	-810	0.6	0.424	0.199	24.35
2186	-800	1.0	0.495	0.347	59.59
2187	-775	1.0	0.120	0.118	11.18
2188	-755	1.0	0.257	0.214	17.96
2189	-730	1.0	0.078	0.097	3.404
2182	-705	2.0	-0.049	0.099	6.551
2183	-690	2.0	-0.062	0.134	8.123
2183	-670	2.0	-0.161	0.081	4.227
2184	-650	2.0	0.144	0.092	4.583
2178	-630	4.0	0.132	0.143	12.57
2179	-616	4.0	0.049	0.130	8.470
2180	-595	4.0	0.175	0.140	17.19
2181	-575	4.0	0.204	0.249	27.52
2205	-510	10.0	-0.305	0.214	36.81
2206	-490	10.0	0.052	0.160	11.41
2207	-475	10.0	-0.024	0.215	19.85
2208	-465	10.0	-0.067	0.187	12.06

LL = 10.0 nA

Run	HV	PreAmp	non-Lin	Error	$\chi^2/6df$
2122	-695	0.1	-0.122	0.120	10.38
2123	-680	0.1	-0.102	0.154	12.09
2124	-665	0.1	-0.024	0.230	30.21
2125	-655	0.1	-0.118	0.422	90.98
2130	-580	0.3	-0.860	0.189	20.04
2131	-565	0.3	-0.856	0.239	44.46
2142	-550	0.3	-0.455	0.465	104.3
2133	-540	0.3	-0.993	0.282	34.38
2138	-525	0.5	-0.913	0.302	44.65
2139	-510	0.5	-1.177	0.307	52.93
2140	-495	0.5	-0.818	0.448	111.9
2141	-480	0.5	-1.012	0.422	89.00
2126	-510	0.6	-1.040	0.313	74.72
2127	-495	0.6	-1.051	0.343	70.39
2128	-480	0.6	-1.578	0.289	60.84
2129	-470	0.6	-1.004	0.356	93.44
2134	-470	1.0	-0.793	0.590	274.1
2135	-455	1.0	-1.332	0.311	90.87
2136	-440	1.0	-1.537	0.457	182.0
2137	-430	1.0	-1.853	0.333	37.05
2118	-410	2.0	-1.865	0.411	89.17
2119	-400	2.0	-1.884	0.408	133.3
2120	-390	2.0	-1.358	0.772	241.9
2121	-380	2.0	-1.541	0.684	318.1

Summary for PMT#4



LL = 0.3 nA

Run	HV	PreAmp	non-Lin	Error	χ^2/6df
1896	-1150	0.5	0.426	0.075	2.420
1897	-1120	0.5	0.320	0.123	5.564
1898	-1080	0.5	0.228	0.093	2.871
1899	-1040	0.5	0.200	0.120	5.120
1905	-1110	0.6	0.502	0.172	7.533
1906	-1080	0.6	0.268	0.125	8.046
1907	-1050	0.6	0.227	0.186	8.355
1908	-1020	0.6	0.389	0.083	2.008
1901	-1010	1.0	0.431	0.102	3.712
1902	-980	1.0	0.182	0.193	16.58
1903	-950	1.0	0.287	0.091	2.936
1904	-920	1.0	0.137	0.112	3.769
1910	-890	2.0	0.027	0.146	7.582
1912	-870	2.0	0.159	0.116	3.802
1913	-840	2.0	-0.154	0.160	4.930
1914	-810	2.0	-0.162	0.151	7.075
1919	-770	4.0	0.072	0.210	7.561
1916	-750	4.0	-0.019	0.120	4.032
1917	-730	4.0	0.133	0.130	3.262
1918	-710	4.0	-0.130	0.117	3.480
1920	-650	10.0	0.139	0.202	8.691
1921	-630	10.0	0.071	0.150	4.912
1922	-610	10.0	0.256	0.144	2.719
1923	-590	10.0	0.223	0.195	6.154

LL = 0.5 nA

Run	HV	PreAmp	non-Lin	Error	χ^2/6df
1863	-1040	0.5	0.393	0.039	0.7648
1865	-1010	0.5	0.289	0.108	4.324
1866	-980	0.5	0.238	0.051	0.9041
1867	-950	0.5	0.360	0.202	19.54
1857	-1000	0.6	0.393	0.064	1.595
1859	-970	0.6	0.354	0.095	3.488
1860	-940	0.6	0.525	0.212	15.26
1861	-920	0.6	0.297	0.142	5.493
1868	-900	1.0	0.344	0.269	29.49
1869	-880	1.0	0.170	0.184	11.66
1870	-850	1.0	0.331	0.062	0.7265
1872	-830	1.0	0.055	0.231	13.05
1873	-800	2.0	0.206	0.148	5.657
1874	-780	2.0	0.055	0.144	7.464
1875	-760	2.0	0.113	0.114	3.686
1876	-740	2.0	0.469	0.237	16.29
1877	-700	4.0	0.095	0.157	6.243
1878	-680	4.0	0.097	0.114	2.977
1879	-660	4.0	0.053	0.146	4.984
1881	-640	4.0	-0.130	0.166	8.138
1883	-590	10.0	-0.266	0.130	3.332
1884	-570	10.0	0.166	0.124	3.616
1885	-550	10.0	-0.237	0.186	6.346
1886	-530	10.0	-0.009	0.197	5.260

LL = 6.0 nA

Run	HV	PreAmp	non-Lin	Error	χ^2/6df
1843	-860	0.1	0.904	0.227	16.77
1844	-840	0.1	0.869	0.251	25.18
1845	-820	0.1	1.269	0.346	26.10
1846	-800	0.1	0.848	0.295	29.19
1847	-860	0.1	1.355	0.247	15.99
1848	-840	0.1	1.054	0.194	14.76
1849	-820	0.1	0.492	0.194	17.84
1850	-800	0.1	1.211	0.541	98.22
1834	-720	0.3	-0.148	0.163	9.668
1835	-700	0.3	-0.179	0.229	9.338
1837	-675	0.3	-0.104	0.242	13.89
1838	-650	0.3	0.205	0.316	24.99
1830	-650	0.5	-0.190	0.111	2.923
1831	-630	0.5	0.148	0.348	39.38
1832	-610	0.5	-0.268	0.213	9.548
1833	-595	0.5	-0.301	0.208	7.082
1839	-645	0.6	-0.079	0.157	6.576
1851	-630	0.6	-0.308	0.084	2.558
1841	-610	0.6	-0.424	0.134	5.048
1842	-590	0.6	0.065	0.383	29.23
1826	-570	1.0	-0.325	0.190	7.729
1827	-555	1.0	-0.397	0.228	9.533
1828	-540	1.0	-0.460	0.221	15.22
1829	-520	1.0	-0.099	0.170	5.098
1819	-500	2.0	-0.428	0.166	5.703
1820	-490	2.0	-0.518	0.124	3.582
1821	-475	2.0	-0.301	0.159	4.882
1822	-460	2.0	-0.469	0.241	9.740

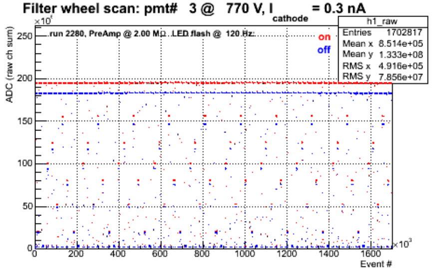
LL = 10.0 nA

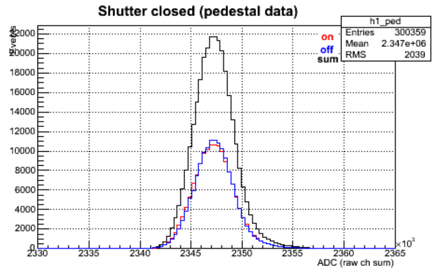
Run	HV	PreAmp	non-Lin	Error	χ^2/6df
1786	-780	0.1	0.038	0.139	9.707
1785	-760	0.1	0.333	0.330	21.84
1782	-740	0.1	-0.163	0.244	18.23
1783	-720	0.1	-0.160	0.187	11.51
1787	-780	0.1	0.262	0.204	22.53
1788	-760	0.1	-0.057	0.092	3.948
1789	-740	0.1	-0.060	0.247	20.74
1790	-720	0.1	-0.417	0.122	7.334
1791	-660	0.3	-0.743	0.171	5.325
1792	-640	0.3	-0.698	0.241	12.76
1793	-620	0.3	-0.672	0.380	23.75
1794	-600	0.3	-0.885	0.325	35.99
1799	-590	0.5	-0.920	0.274	26.76
1800	-570	0.5	-0.901	0.271	16.07
1801	-550	0.5	-1.015	0.320	33.61
1802	-530	0.5	-1.231	0.265	14.08
1795	-575	0.6	-1.042	0.254	10.40
1796	-555	0.6	-1.205	0.164	5.487
1803	-535	0.6	-1.378	0.253	16.20
1798	-520	0.6	-1.446	0.374	21.15
1804	-520	1.0	-0.998	0.411	29.96
1805	-505	1.0	-1.421	0.379	23.99
1806	-490	1.0	-1.506	0.458	25.02
1807	-480	1.0	-1.780	0.528	53.54
1808	-460	2.0	-1.530	0.253	12.60
1809	-450	2.0	-1.865	0.252	16.29
1810	-435	2.0	-1.870	0.376	26.69
1811	-425	2.0	-1.823	0.348	17.32

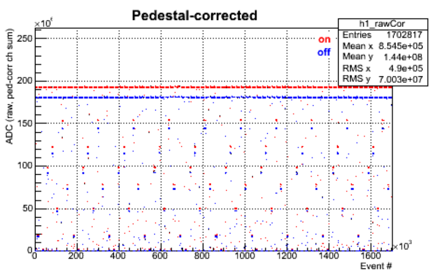
A Different Approach of Measurement (from Kent)

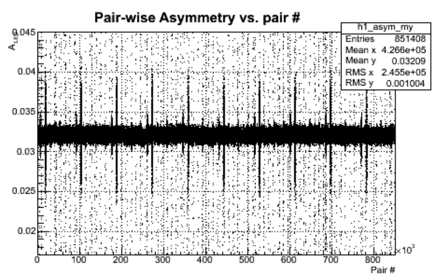
- Go back to 100 % transmission setting after each filter measurement
- Each filter stays in its position for 20 sec
- 100 % transmission position stays in its position for 60 sec
- Shutter remains close for 8 sec during each filter change
- Filter wheel rotates 10 cycles
- Takes about 2 hrs to collect 1.7 M events

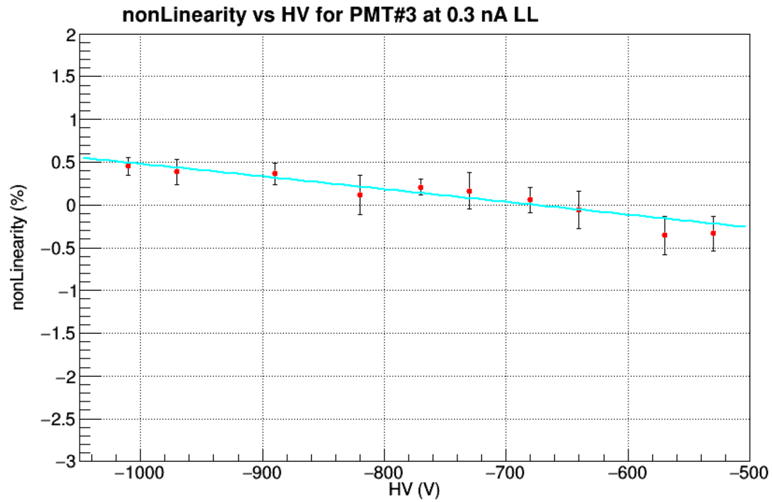
Run	HV	PreAmp	non-Lin	Error	χ^2/6df
2289	-1010.0	0.5	0.454	0.102	1.571
2290	-970.0	0.5	0.387	0.144	8.671
2287	-890.0	1.0	0.364	0.127	1.943
2288	-820.0	1.0	0.018	0.224	4.546
2280	-770.0	2.0	0.210	0.095	3.228
2281	-730.0	2.0	0.165	0.216	3.021
2282	-680.0	4.0	0.060	0.148	4.632
2284	-640.0	4.0	-0.053	0.219	3.967
2285	-570.0	10.0	-0.357	0.223	11.08
2286	-530.0	10.0	-0.335	0.200	8.374











Summary and Future Plans

- So far, results are very promissing; we should meet or surpass PMT non-linearity systematic error requirements
- PMT non-linearity shows a linear relation with high voltage
- There is always a certain high voltage above which the non-linearity changes its sign
- Results from constant temperature technique agree with those from our regular measurement technique
- Planning to repeate the measurements
- Still planning to explore the Qweak style non-linearity measurements which use 3 LEDs (two of them flashing at different rates and one steady)

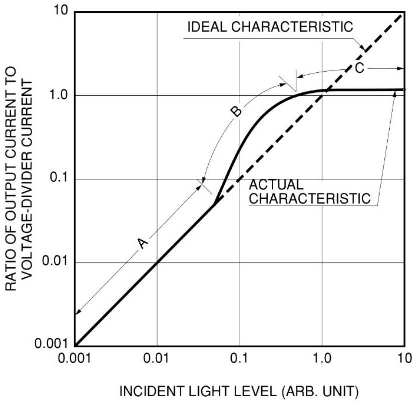
THANK YOU

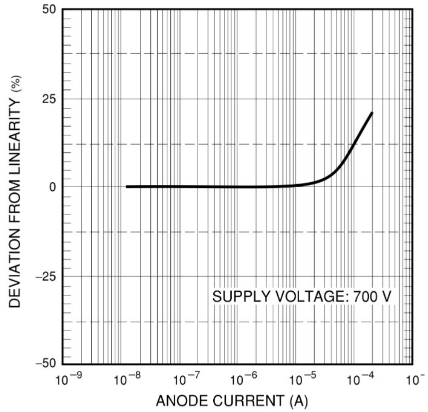
All the plots of the study can be found at:

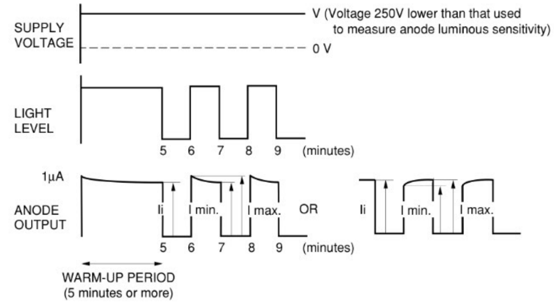
daq3.physics.isu.edu/linearity/PMT.html.

Extra Slides

PMT characteristics from Hamamatsu handbook



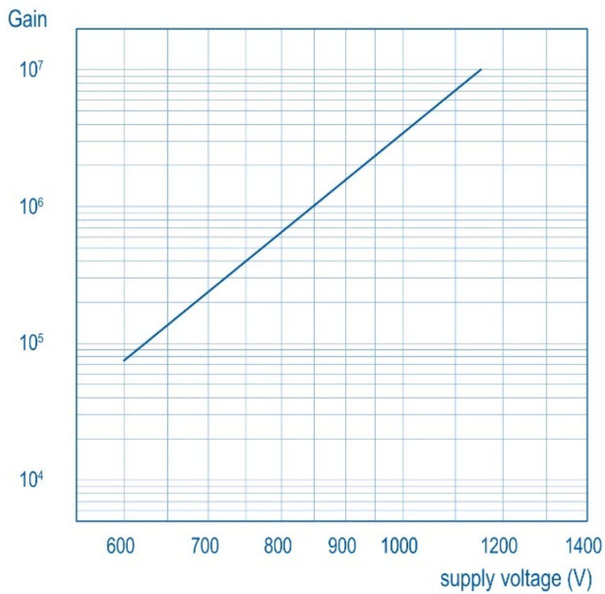


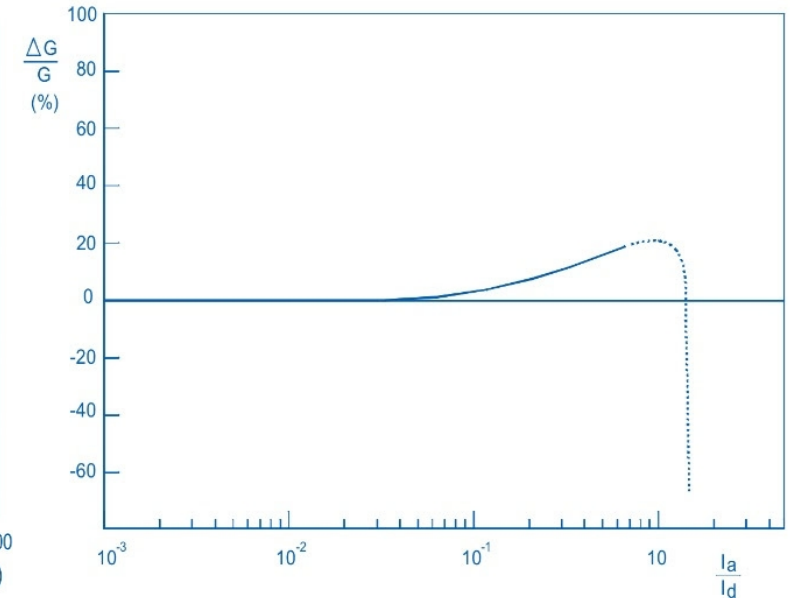


- At high currents, space charge can influence the electron trajectory, causing collection losses.
- Light level > certain level – PMT output becomes saturated and is no longer proportional to the light level.
- Light hysteresis and voltage hysteresis of the PMT.
- Signal to noise ratio of the PMT.
- Drift (time stability) – warm up helps minimize.
- PMT operation stability depends on the total stability of the power supply characteristics (drift, ripple, temperature, input regulation, load regulation).

hamamatsu.com/resources/pdf/etd/PMT_ handbook_v3aE.pdf.

PMT characteristics from Photonis





- PMT gain varies as a power of the supply voltage:

$$\frac{G_2}{G_1} = \left(\frac{V_2}{V_1}\right)^{\alpha N}$$

- α ε [0.6,0.8], N is the number of dynodes.
- Gain varies as a function of I_a/I_d. I_a is the actual anode current and I_d is the divider current.

particle.korea.ac.kr/lab/cata_ basic.pdf.