PMT Non-Linearity Studies at ISU

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Outline

- Introduction (Asymmetry and non-linearity)
- Motivations
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- Qweak ADC Details
- Steps and approaches in Non-Linearity Measurement
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Introduction (Asymmetry and non-linearity)

LED

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

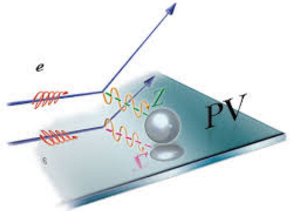
$A_{LED} = A_{true}(1 + \beta N_{avg})$ is the fit function.

- $N^{\pm} = N_S^{\pm}(1+\beta N_S^{\pm})$ 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

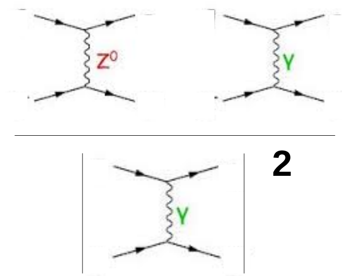
- Polarized beam with unpolarized target.
- Measurements in opposite helicity states.
- Asymmetry of cross sections:



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

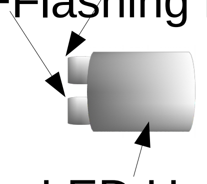
$$\sigma_{R(L)} = \frac{d\sigma_{R(L)}}{d\Omega} \propto (S_\gamma + S_Z^{R(L)})^2$$

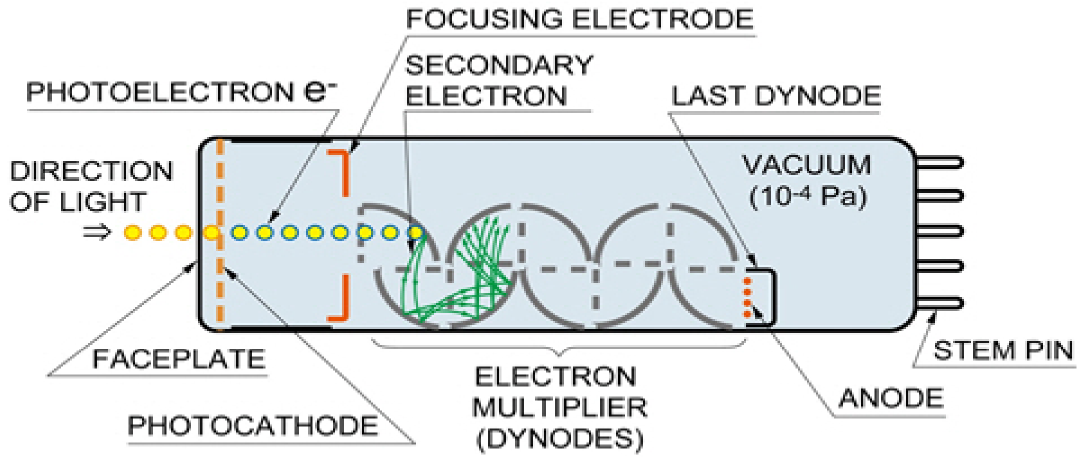
∝



$\sim \frac{10^{-4}\,Q^2}{GeV^2}$

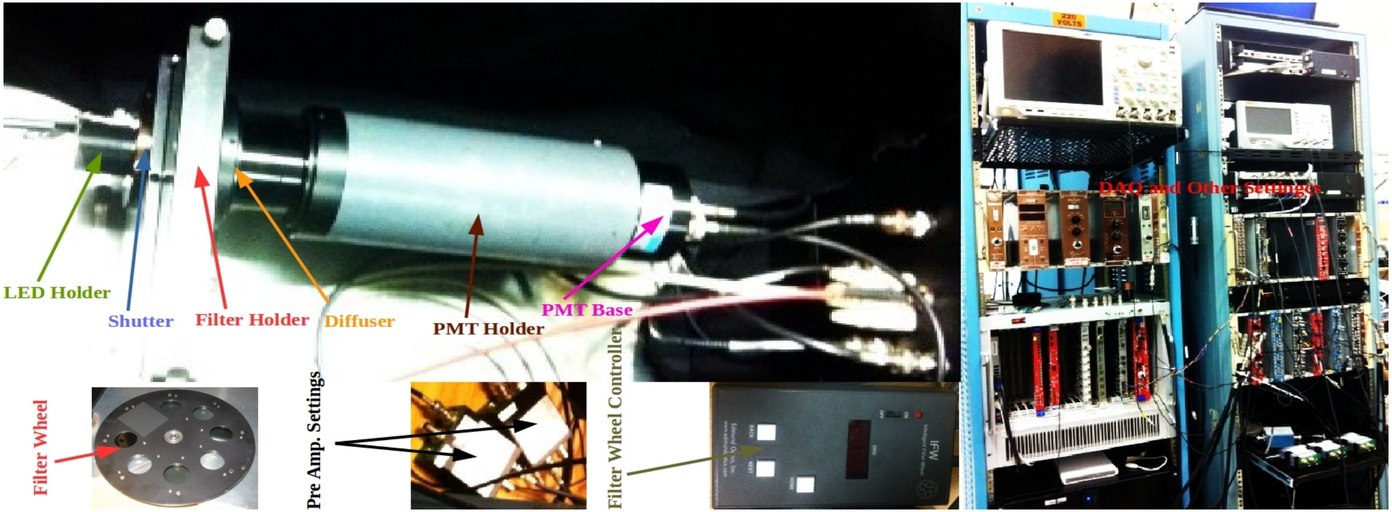
Motivations





- PMTs tested here will be used in the PREx-II/CREx detectors
- PREx-II/CREx are high-precision experiments with statistics dominated uncertainties
- PMT non-linearity is one of the important sources of systematic errors in PREx-II/CREx experiments
- PMT non-linearity will be at most 0.3 % (CREx) and 1 % (PREx-II).
- PMTs should show the best linear response with the LL equivalent to Cerenkov light that it receives during PREx-II/CREx experiments

Black Box Setup and Integrating DAQ Systems



- 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, 78, 50, 40, 25, 10, 0)% 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)

Qweak ADC Details

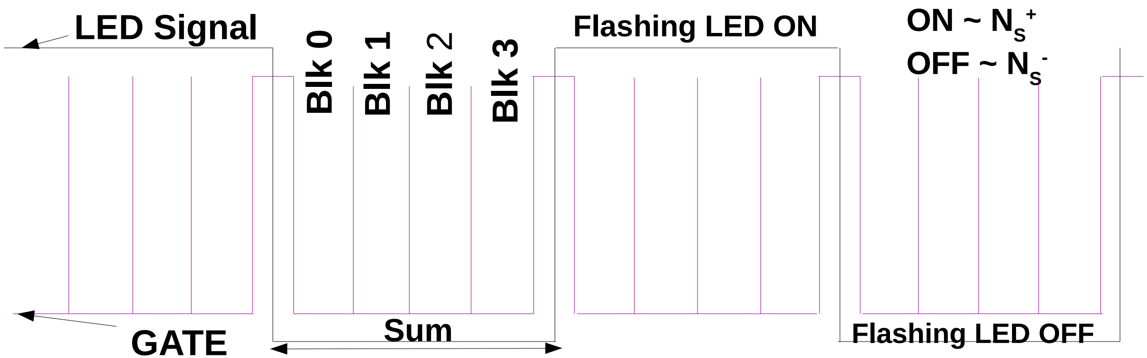


Figure: DAQ response sampled in four blocks.

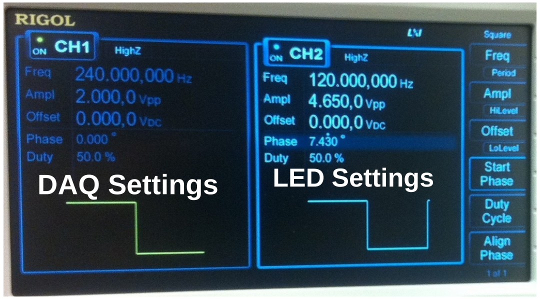


Figure: Function Generator settings.

- 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

Selection of Light Level (Preliminary)

- Upstream Quartz thickness = 6 mm
- Downstream Quartz thickness = 10 mm

Results from Testbeam (Mainz Germany) w/o wrapping give:

- Peak PEs upstream = 37 with ~20% resolution
- Peak PEs downstream = 65 with ~17% resolution

PREx-II

- Rate = 1 GHz
- LL with upstream quartz = 1GHz*37*e ~ 6 nA
- LL with downstream quartz ~ 10 nA

CREx

- Rate = 50 MHz
- LL with upstream quartz = 50MHz*37*e ~ 0.3 nA
- LL with downstream quartz ~ 0.5 nA
- I have tested 0.7 nA, 3 nA, 7 nA, and 14 nA LLs so far

Steps in Data Collection

- LL controlled by HAPPEx timer DAC12, 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 (40 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
- Quartet and non-Quartet approaches were tried for 7 nA LL
- An automated c++ code has been developed that removes any “unclean” data during filter rotation and analyzes the rest
- The pedestal correction was performed in three different ways:

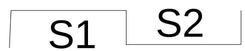
  (1) include all pedestal data and subtract the same average for all data points (Note, pedestal data was collected anytime shutter closed)

  (2) like (1) but for even and odd separately

  (3) include only the pedestal data just before and just after a filter change (to pedestal-correct that specific filter)
- All three approaches were tried for 14 nA LL, and all gave same/consistent results – so we now only use method (1)

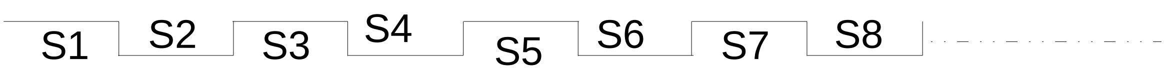
Steps and Approaches in Data Analysis (contd.)

- For non-Quartet approach, the data from two consecutive gates were used to calculate simple pair-wise asymmetry



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

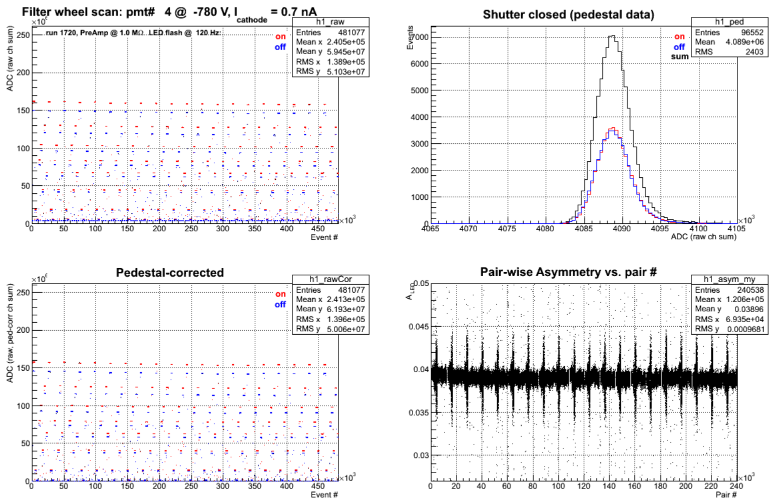
- For Quartet approach, the data from eight consecutive gates was used to determine asymmetry. Asymmetry is formed between the even and odd groups – gives flavor of 30 Hz flipping

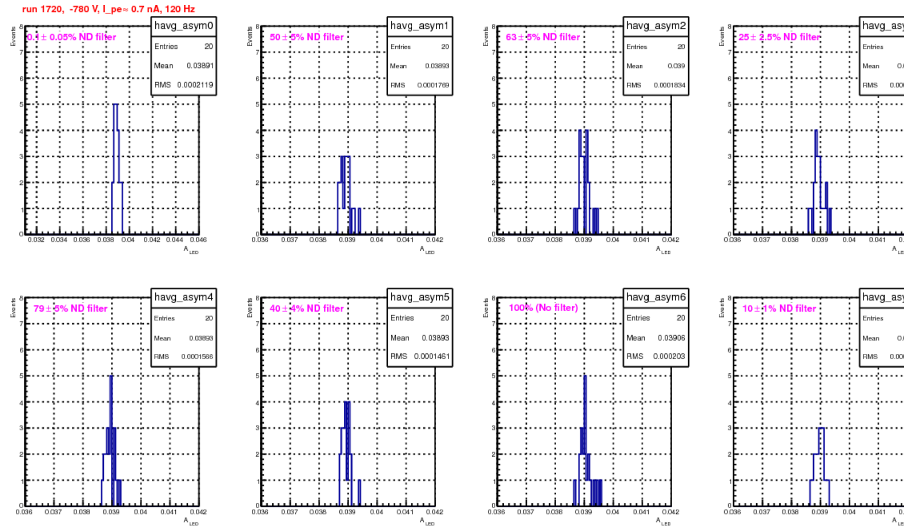


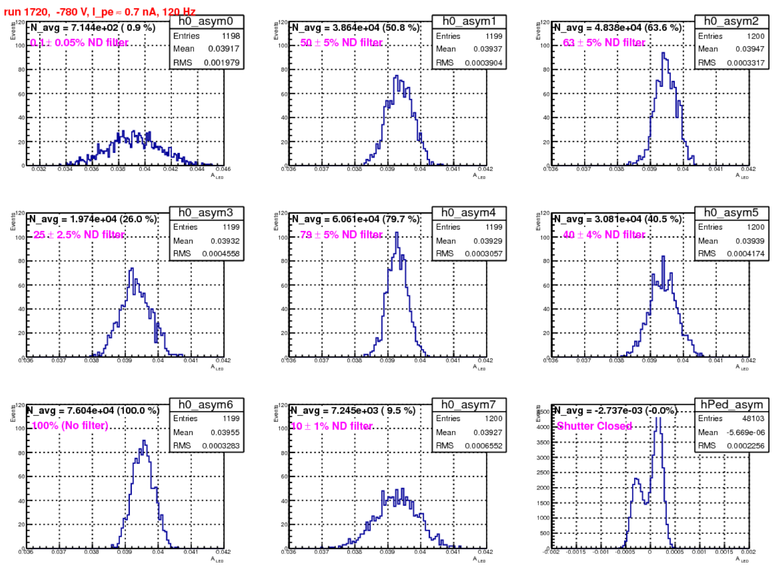
$$A = \frac{\sum_{even}^{4} S_n - \sum_{odd}^{4} S_n}{\sum_{even}^{4} S_n + \sum_{odd}^{4} S_n}$$

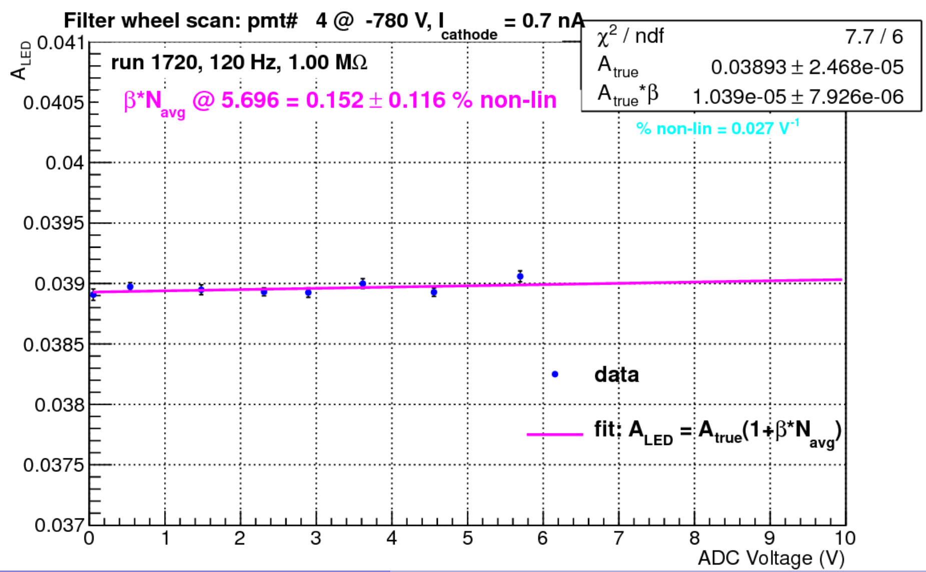
0.7 nA LL Measurement

- 1.0 MΩ preAmp and -780 V High Voltage.



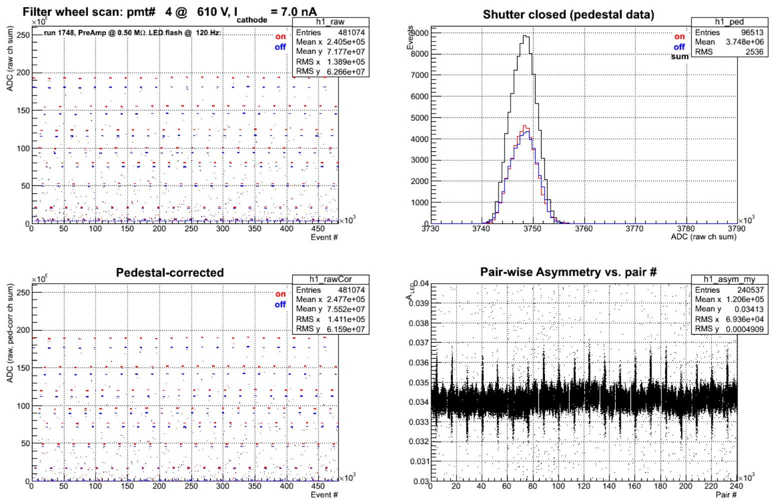


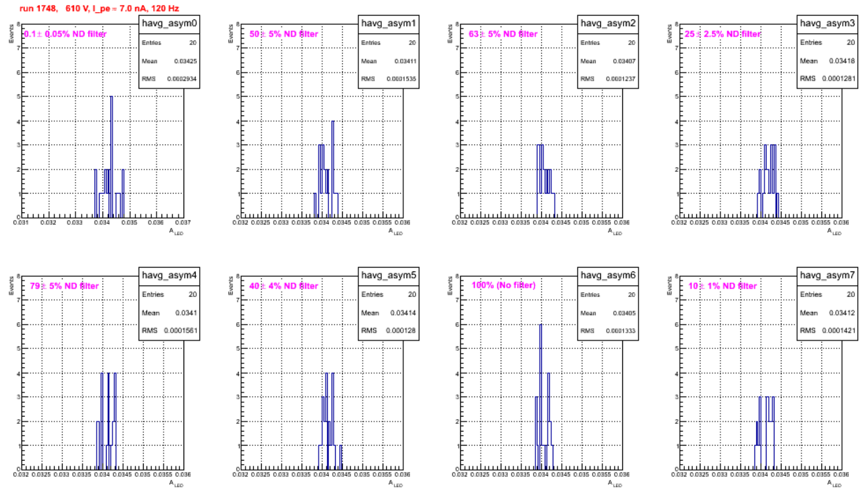


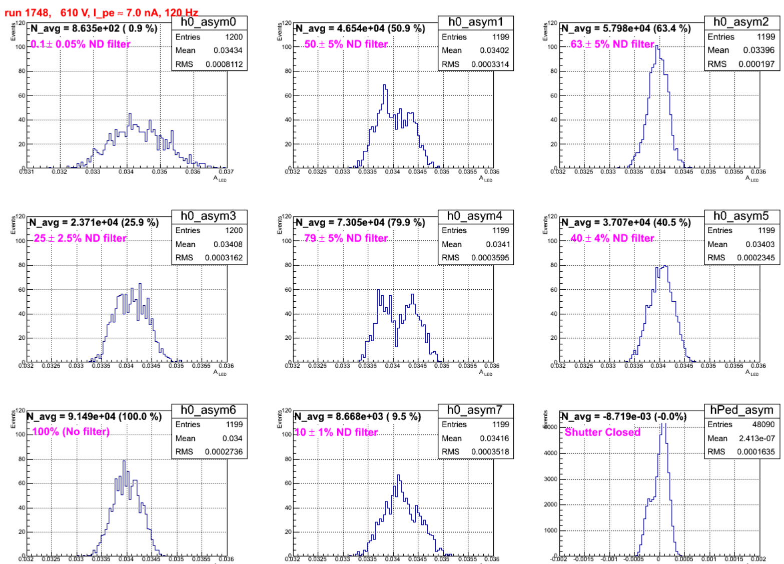


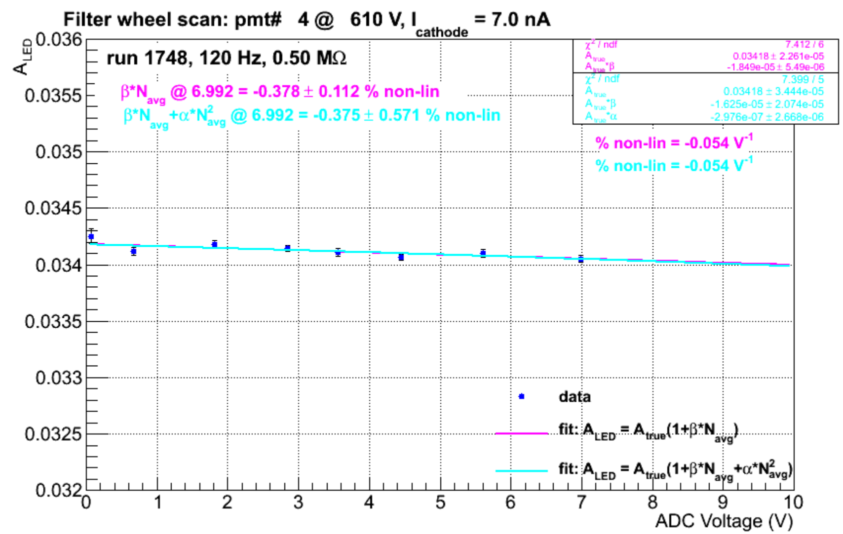
7 nA LL Measurement

- 0.5 MΩ preAmp and -610 V High Voltage.



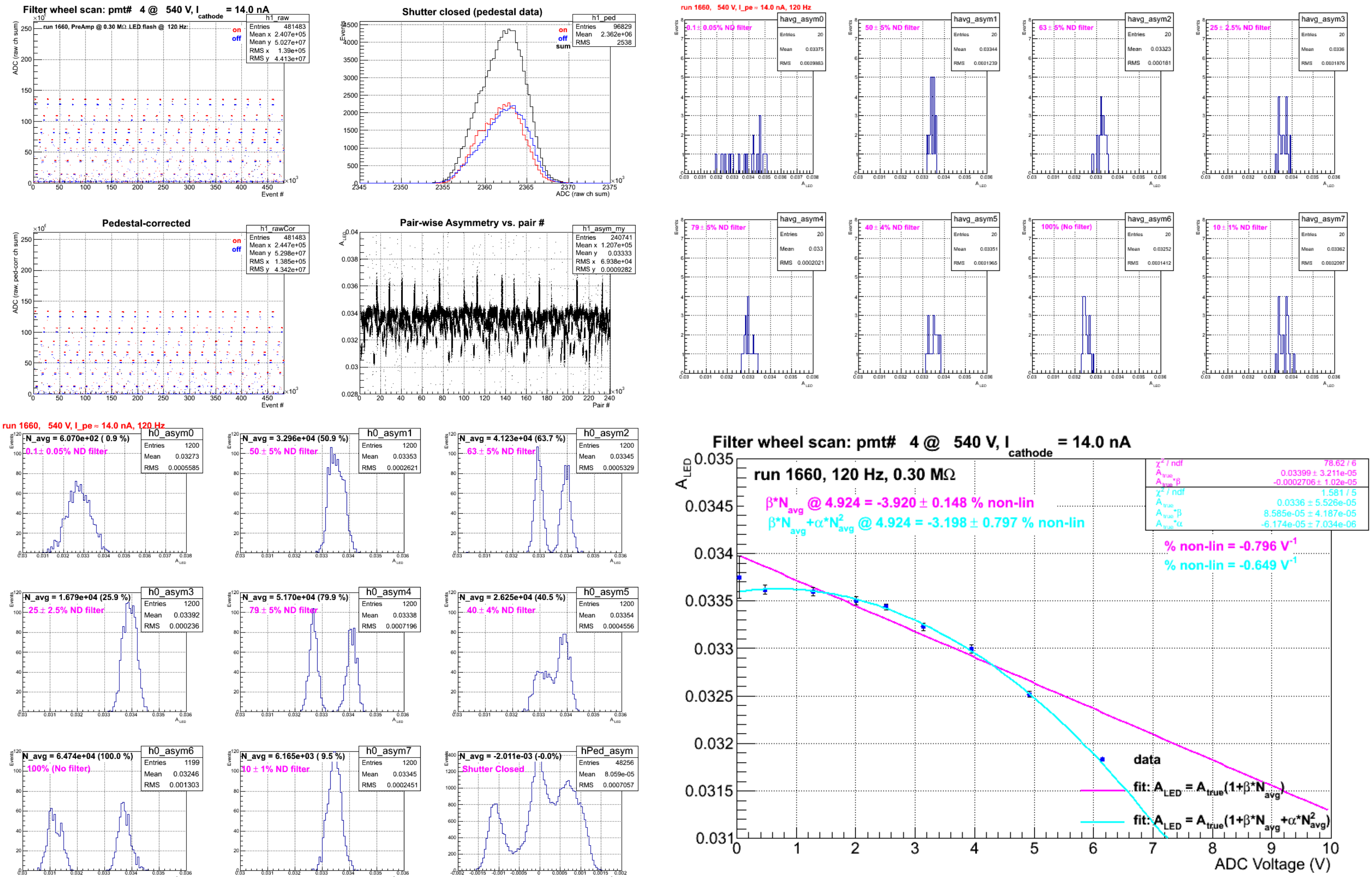




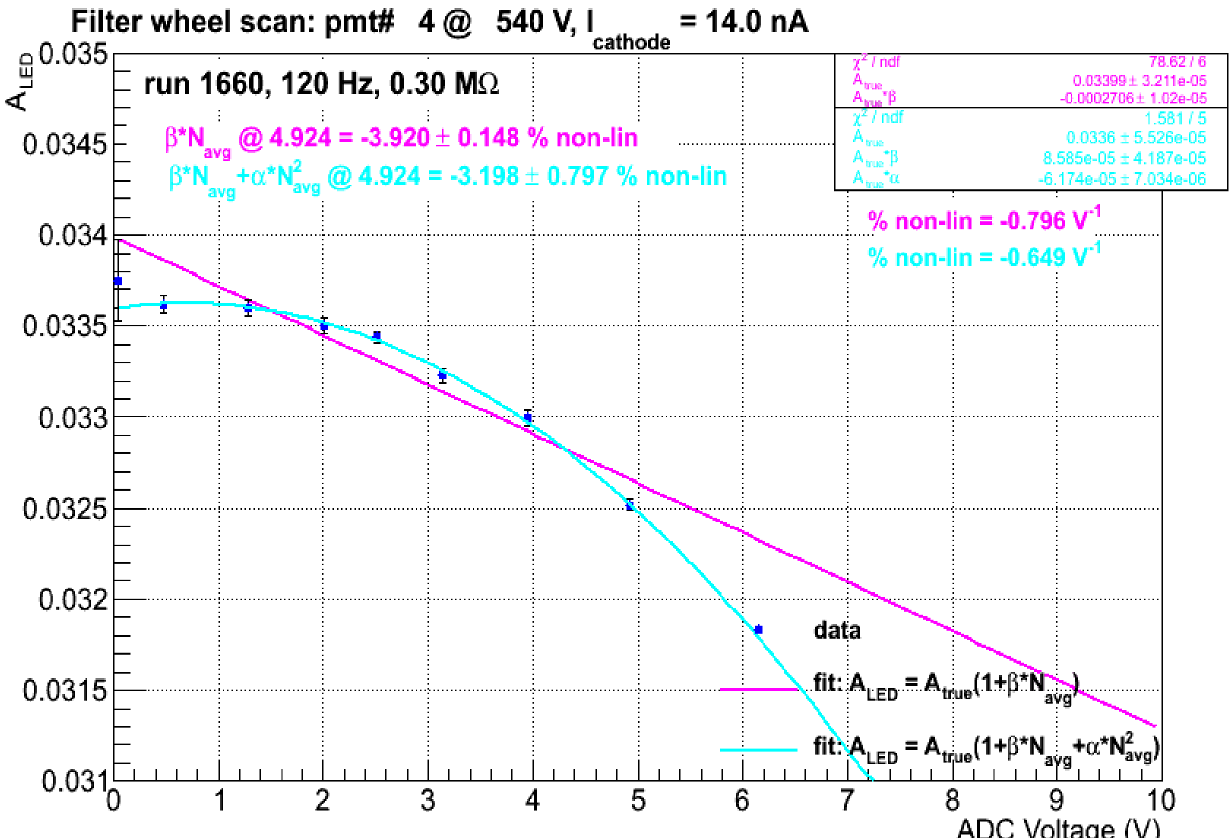


14 nA LL Measurement

- 0.3 MΩ preAmp and -540 V High Voltage.



Need of Second Order non-linearitv



- Fit function with first order non-linearity:

$$A_{LED} = A_{true}\left(1 + \beta N_{avg}\right)$$

is good for lower LLs.

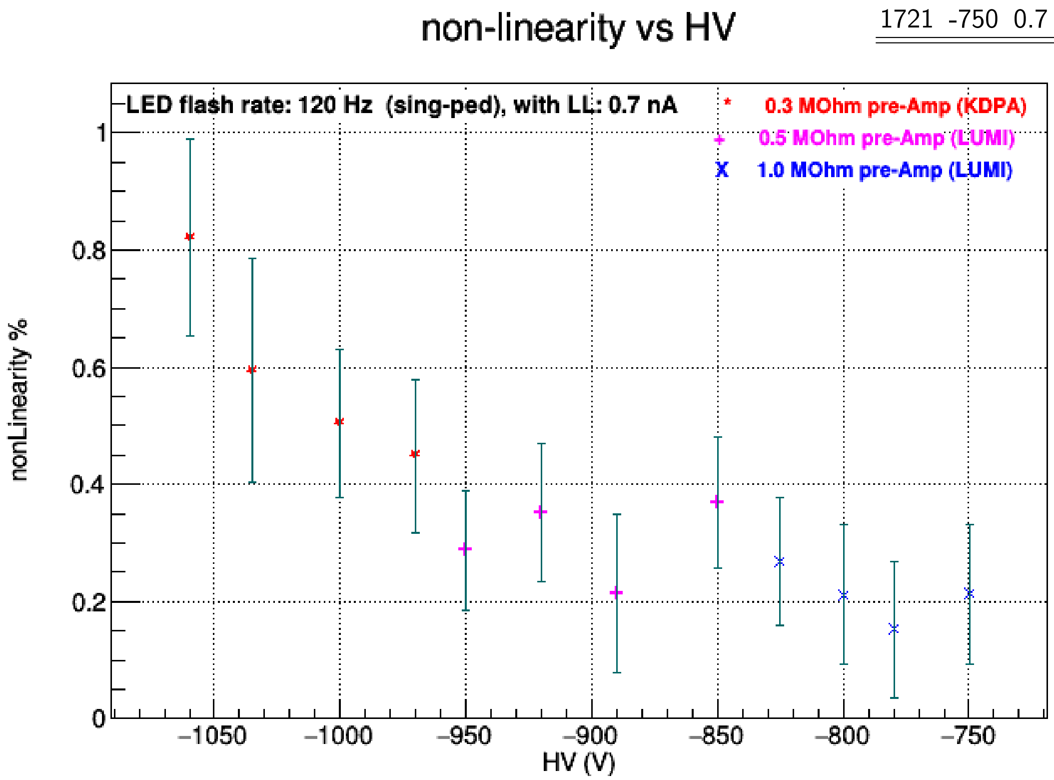
- But for higher LLs (14 nA), fit function with second order correction:

$$A_{LED} = A_{true}\left(1 + \beta N_{avg} + \alpha N_{avg}^2\right)$$

fits much better. (However, overall error is much higher???)

Summary Table (0.7 nA LL)

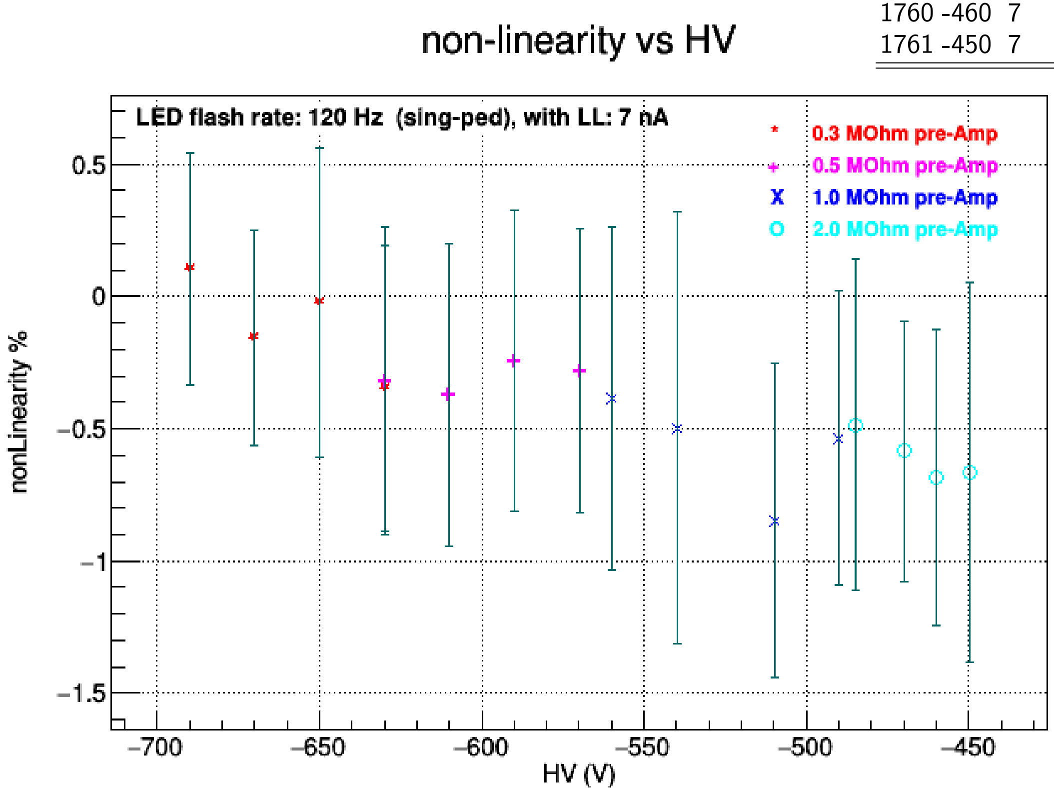
Run	HV	LL	PreAmp	Navg	non-Linearity	non-Linearity/V	X2/ndf
1710	-1060	0.7	0.3	104400	0.821±0.169	0.103	2.220/6
1708	-1035	0.7	0.3	92420	0.594±0.192	0.084	1.213/6
1706	-1000	0.7	0.3	74430	0.503±0.127	0.089	18.30/6
1713	-970	0.7	0.3	64570	0.448±0.130	0.091	1.245/6
1711	-950	0.7	0.5	96510	0.287±0.103	0.039	5.926/6
1712	-920	0.7	0.5	79540	0.352±0.117	0.058	1.464/6
1704	-890	0.7	0.5	71150	0.214±0.136	0.039	10.79/6
1702	-850	0.7	0.5	53790	0.369±0.112	0.090	10.06/6
718	-825	0.7	1.0	101200	0.267±0.109	0.035	6.506/6
1719	-800	0.7	1.0	87940	0.211±0.119	0.031	7.054/6
1720	-780	0.7	1.0	74670	0.152±0.116	0.027	7.700/6
1721	-750	0.7	1.0	61430	0.213±0.119	0.046	6.454/6



* smaller non-linearity for larger preAmp gain and smaller HV.

Summary Table (7 nA LL)

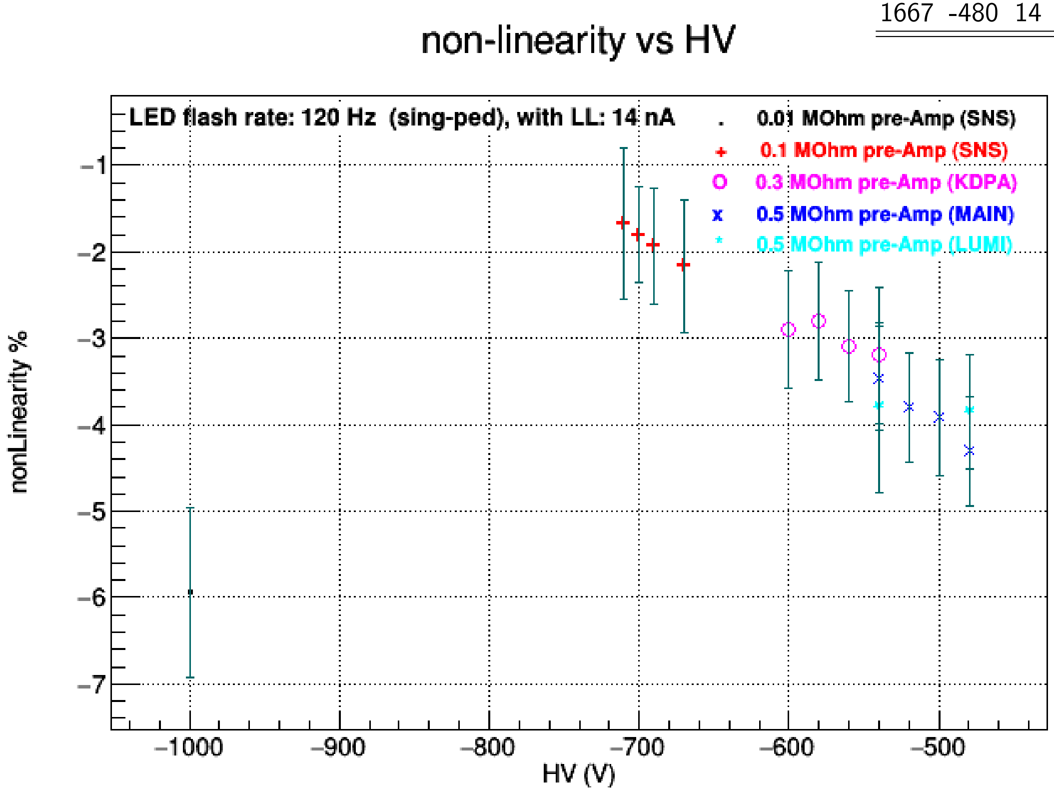
Run	HV	LL	PreAmp	Navg	non-Linearity	non-Linearity/V	X2/ndf
1743	-690	7	0.3	109800	0.102±0.439	-0.012	8.261/5
1744	-670	7	0.3	90000	-0.156±0.408	-0.023	18.12/5
1745	-650	7	0.3	78090	-0.025±0.585	-0.004	13.51/5
1746	-630	7	0.3	66730	-0.347±0.540	-0.068	14.92/5
1747	-630	7	0.5	108700	-0.321±0.581	-0.039	3.652/5
1748	-610	7	0.5	91650	-0.375±0.571	-0.054	7.399/5
1750	-590	7	0.5	73170	-0.243±0.568	-0.043	18.53/5
1751	-570	7	0.5	61010	-0.281±0.539	-0.060	6.255/5
1753	-560	7	1.0	118700	-0.387±0.648	-0.043	8.446/5
1754	-540	7	1.0	96220	-0.497±0.817	-0.068	1.341/5
1756	-510	7	1.0	71480	-0.847±0.592	-0.155	0.9393/5
1757	-490	7	1.0	58620	-0.535±0.555	-0.120	5.859/5
1758	-485	7	2.0	106600	-0.484±0.627	-0.060	6.619/5
1759	-470	7	2.0	89840	-0.585±0.490	-0.085	8.503/5
1760	-460	7	2.0	79900	-0.687±0.559	-0.113	8.788/5
1761	-450	7	2.0	71210	-0.663±0.719	-0.122	11.59/5



* smaller non-linearity for smaller preAmp gain and higher HV.

Summary Table (14 nA LL)

Run	HV	LL	PreAmp	Navg	non-Linearity	non-Linearity/V	X2/ndf
1643	-1000	14	0.01	68950	-5.941±0.980	-1.129	189.4/5
1642	-710	14	0.1	95810	-1.669±0.870	-0.228	8.623/5
1637	-700	14	0.1	94070	-1.798±0.549	-0.251	10.96/5
1651	-690	14	0.1	74550	-1.928±0.672	-0.339	10.62/5
1638	-670	14	0.1	73150	-2.163±0.767	-0.388	6.173/5
1656	-600	14	0.3	111400	-2.905±0.682	-0.342	4.381/5
1657	-580	14	0.3	94320	-2.802±0.674	-0.389	7.933/5
1658	-560	14	0.3	78190	-3.099±0.640	-0.519	5.036/5
1660	-540	14	0.3	64550	-3.198±0.797	-0.649	1.581/5
1661	-540	14	0.5	106600	-3.460±0.604	-0.418	8.637/5
1663	-520	14	0.5	88860	-3.800±0.640	-0.561	10.98/5
1664	-500	14	0.5	72020	-3.913±0.668	-0.712	4.415/5
1666	-480	14	0.5	56870	-4.307±0.636	-0.993	29.52/5
1662	-540	14	0.5	108600	-3.796±0.985	-0.467	4.45/5
1667	-480	14	0.5	57230	-3.849±0.665	-0.882	14.42/5



- smaller non-linearity for smaller preAmp gain and higher HV.

Issues and Questions

- Should we think about changing quartz thickness for PREx-II? 10 nA LL will be near the acceptable limit.
- Is it a good idea to study linearity to the second order?
- How to handle error (and interpret χ^2) on non-linearity properly?
- Why 2^{nd} order fits give much higher non-linearity error?
- Could use more precise calibration of LL:

  $\rightarrow$ calibrate picoammeter.

  $\rightarrow$ use R7723 PMT with unity base, not R375 PMT.
- Question of preAmp bandwidth? What is best? Does it matter?

  $\rightarrow$ We need a working KDPB preAmp to help test.

Summary and Future Plans

- So far, results are very promising; we will meet or surpass PMT non-linearity systematic error requirements.
- At 7 nA and 14 nA LLs, get smaller non-linearity for smaller preAmp gain and higher HV.
- At 0.7 nA LL, get smaller non-linearity for larger preAmp gain and smaller HV.
- Results from quartet analysis were not significantly different than those from non-quartet after implementing the 20 cycle data collection technique.
- Different approaches of subtracting pedestal didn't cause any difference in the non-linearity result.
- Planning to study non-linearity at other LLs and with different PMTs.
- Constant temperature data collection technique; exploring now.
- Also, 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/Linearity.html.

Extra Slides

Steps in Error Analysis

First Order non-Linearity

1. $A_{LED} = A_{true}(1 + \beta * N_{avg})$

2. $N = \beta * N_{avg} = \frac{p_1}{p_0} * N_{avg} * 100\%$

Here, p_1 and p_0 are the fit parameters

3. $\frac{\partial N}{\partial p_0} = -\frac{p_1}{p_0^2} * Navg * 100\%$

4. $\frac{\partial N}{\partial p_1} = \frac{1}{p_0} * Navg * 100\%$

5. $\partial N = \sqrt{(\partial p_1)^2 (\frac{\partial N}{\partial p_1})^2 + (\partial p_0)^2 (\frac{\partial N}{\partial p_0})^2}$

6. $\partial N = \sqrt{(\frac{\partial p_1}{p_1})^2 + (\frac{\partial p_0}{p_0})^2} * \frac{p_1}{p_0} * N_{avg} * 100\%$

Second Order non-Linearity

1. $A_{LED} = A_{true}(1 + \beta * N_{avg} + \alpha * N_{avg}^2)$

2. $N = \beta * N_{avg} + \alpha * N_{avg}^2$

$$N = \frac{p_1}{p_0} * N_{avg} * 100\% + \frac{p_2}{p_0} * N_{avg}^2 * 100\% = x + y$$

Here, p_2, p_1 and p_0 are the fit parameters

3. $\partial N = \sqrt{(\partial x)^2 + (\partial y)^2}$

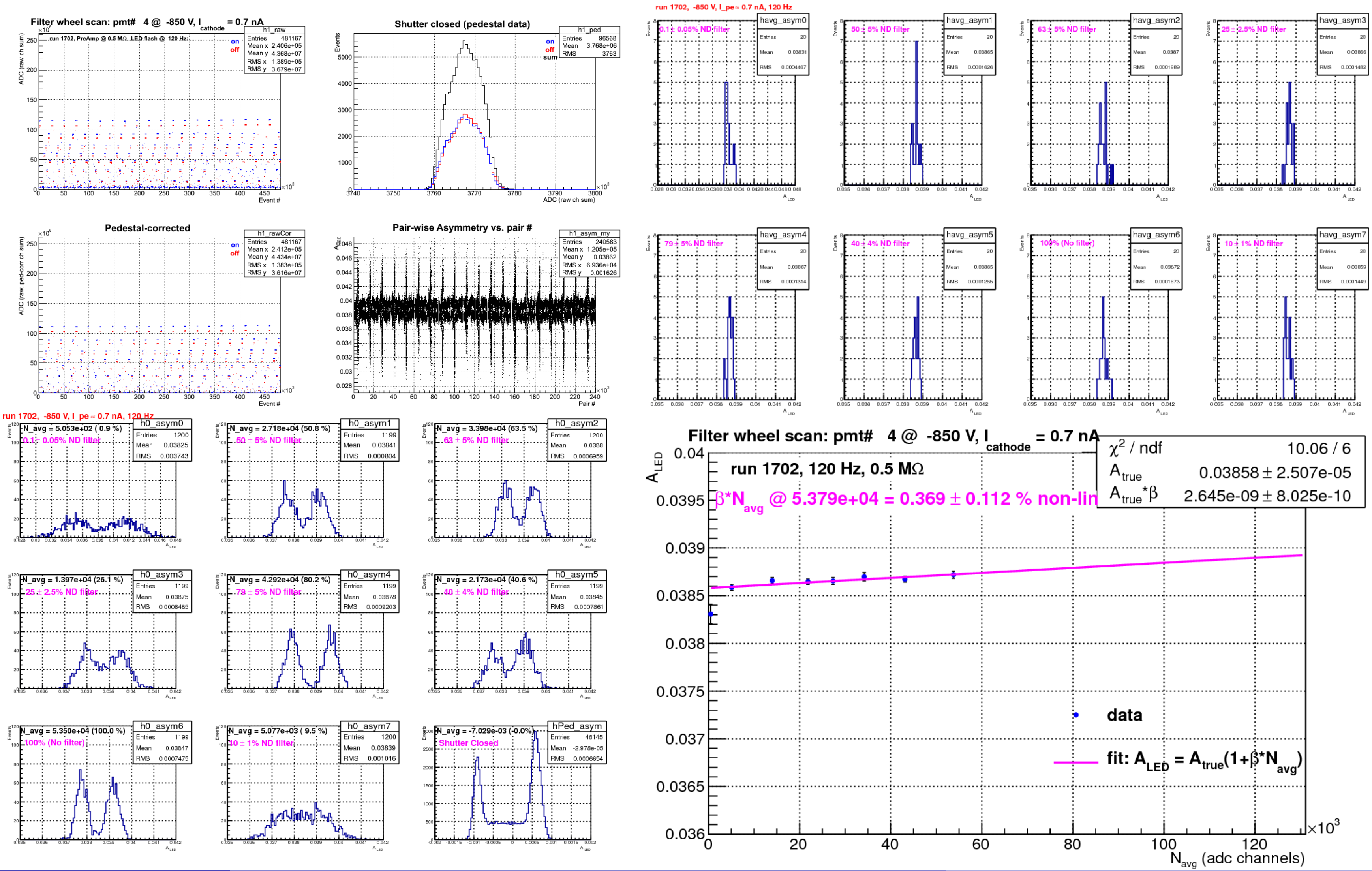
4. $\partial x = \sqrt{(\frac{\partial p_1}{p_1})^2 + (\frac{\partial p_0}{p_0})^2} * \frac{p_1}{p_0} * N_{avg} * 100\%$

5. $\partial x = \sqrt{(\frac{\partial p_2}{p_2})^2 + (\frac{\partial p_0}{p_0})^2} * \frac{p_2}{p_0} * N_{avg}^2 * 100\%$

6. $\partial N = \sqrt{[(\frac{\partial p_1}{p_1})^2 + (\frac{\partial p_0}{p_0})^2] * p_1^2 + [(\frac{\partial p_2}{p_2})^2 + (\frac{\partial p_0}{p_0})^2] * p_2^2 * N_{avg}^2} * \frac{N_{avg}}{p_0} * 100\%$

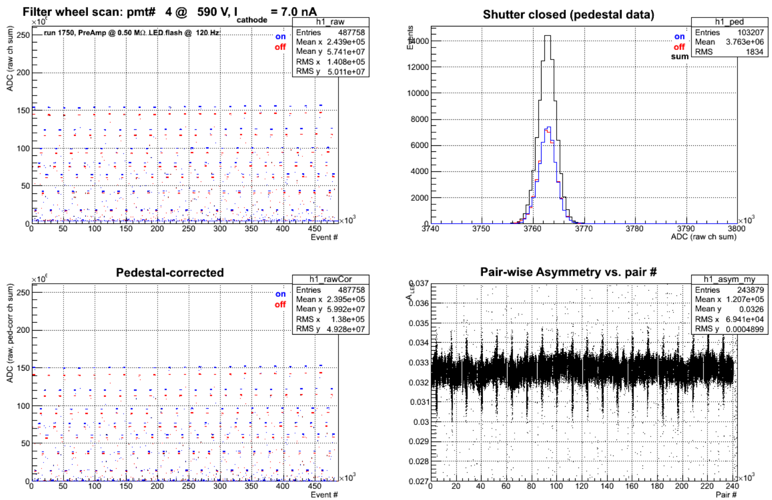
0.7 nA LL Measurement

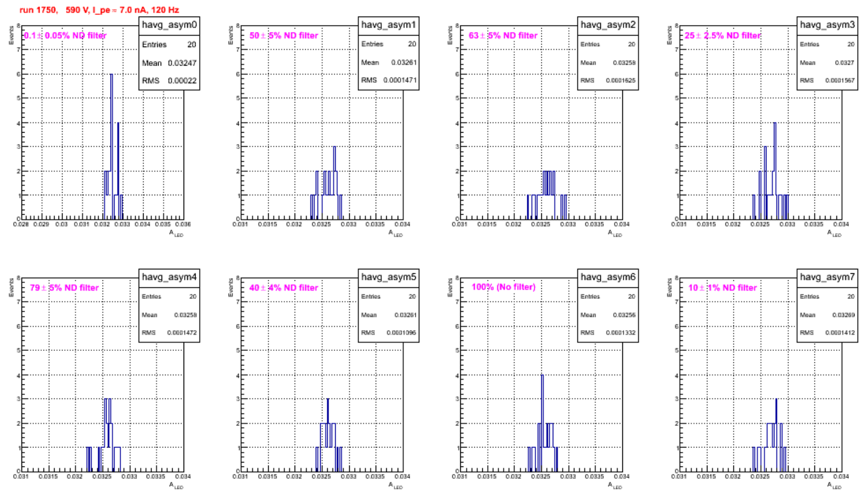
- 0.5 MΩ preAmp and -850 V High Voltage.

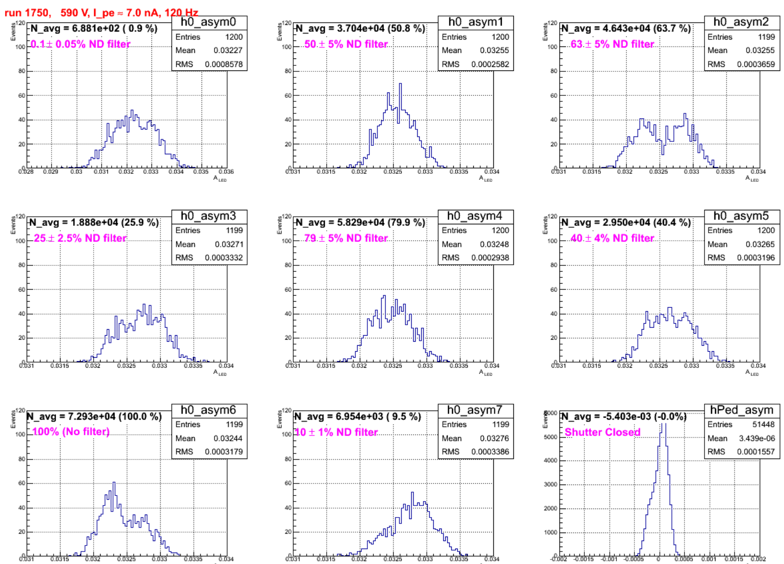


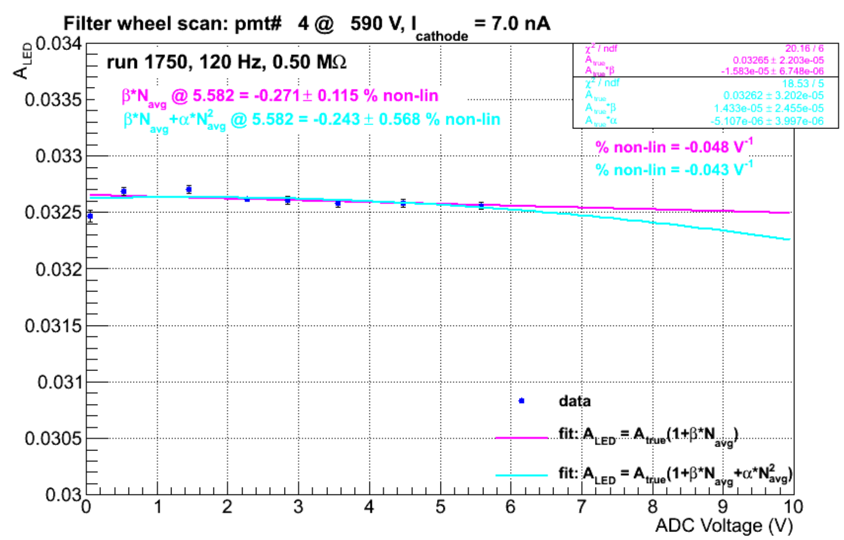
7 nA LL Measurement

- 0.5 MΩ preAmp and -590 V High Voltage.









14 nA LL Measurement

- 0.01 MΩ preAmp and -1000 V High Voltage.