SiPM Saturation

AHCAL Meeting DESY 2017

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SiPM Saturation – Outline

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- Introduction & Definitions
- Crosstalk measurement
- Saturation measurement
- Implementation in CALICE offline analysis?

	SiPM	N_{total}	pixel pitch [μm]	sensitive area [mm^2]	typical gain	trenches
On SMD HBUs since 2016	MPPC S13360 -1325PE	2668	25	1.3×1.3	$7.0 \cdot 10^5$	yes
On first SMD HBU 2015	MPPC S12571 -25P	1600	25	1×1	$5.15 \cdot 10^5$	no
	MPPC S12571 -50P	400	50	1×1	$1.25 \cdot 10^6$	no
	MPPC S12571 -100P	100	100	1×1	$2.8 \cdot 10^6$	no

Introduction: SiPM Crosstalk, Saturation & N_{seed}

100 pixel SiPM:

$\epsilon_{PDE} = 0.5$	efficiency
$\mu_C = 1.25$	correlated noise (XT)

← 25% Crosstalk

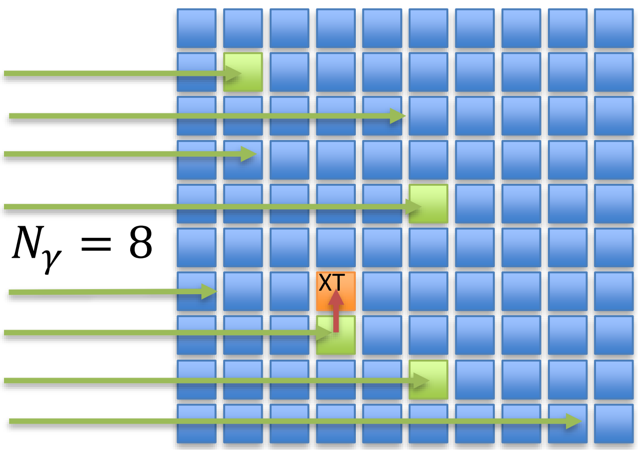
Without saturation
With crosstalk

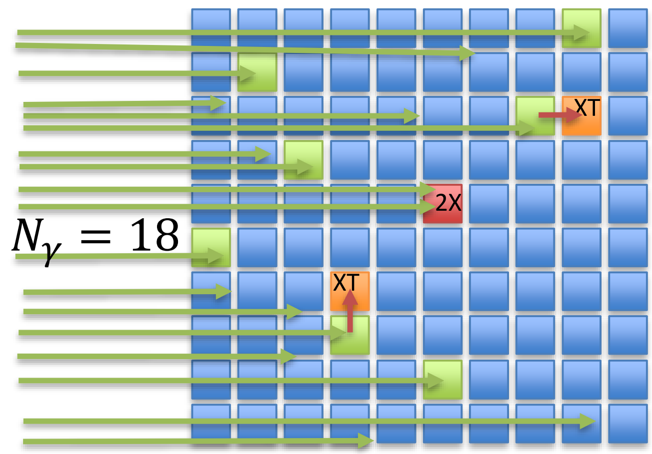
Calibration region

With Saturation
With crosstalk

Saturation region

$$N_{seed} := N_\gamma \cdot \varepsilon_{PDE}$$





$N_{fired} \stackrel{\text{def}}{=} N_{fired}^{linear} = 5$ (w/o saturation, w/ XT)

XT correction: $N_{fired}^{linear} / \mu_C$

$N_{seed} = 4$ (w/o saturation, w/o XT)

$N_{fired} = 10$ (w/ saturation & w/ XT)

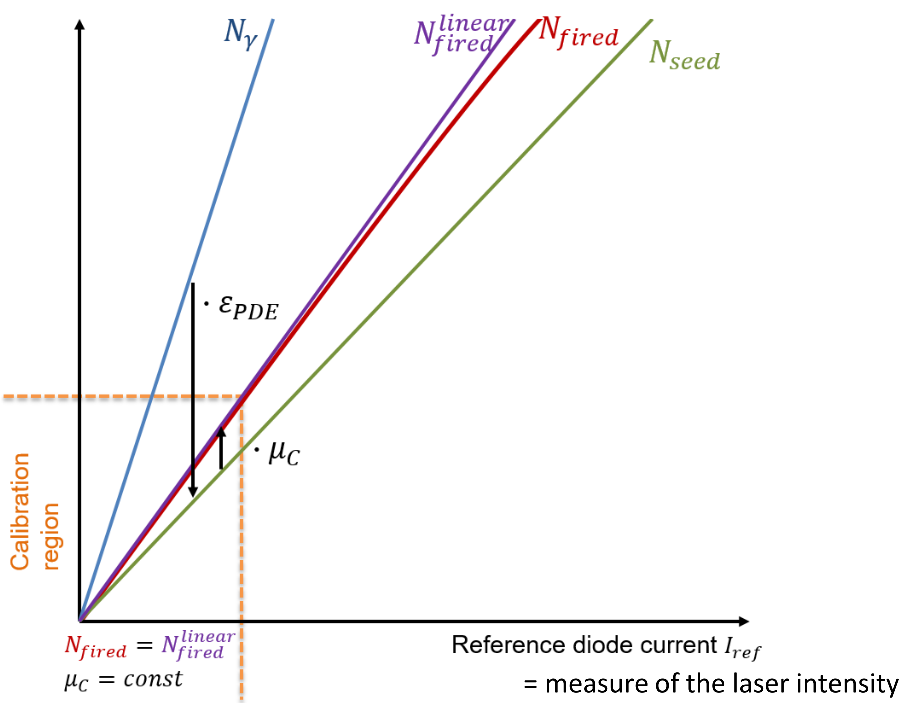
Advanced function which handles saturation & XT

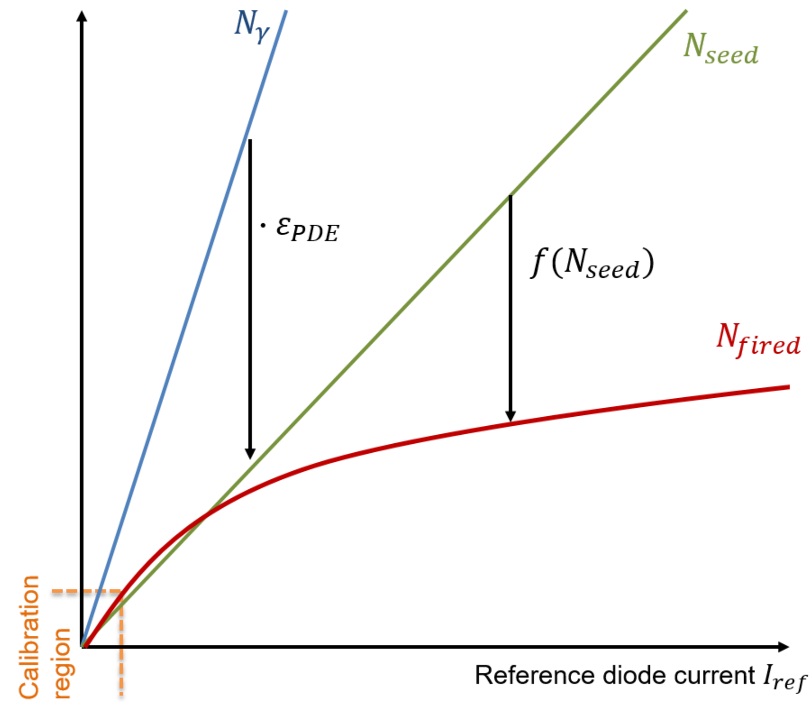
$N_{seed} = 9$ (w/o saturation, w/o XT)

Definitions

Number of seeds N_{seed}:
Number of photons, which hit the sensitive area of the SiPM and could trigger an avalanche (including PDE) in case of linear behavior (no multi-hits on pixels).
$\boldsymbol{N_{seed} \coloneqq N_\gamma \cdot \varepsilon_{PDE}}$

N_γ: *Number of incident photons*
ε_{PDE}: *Photon Detection Efficiency*
μ_C: *Correlated noise, in first order defined as*: $\mu_C = 1 + E(XT)$
N_{fired}: *Number of pixels fired (main observable)*
f: *Function describing saturation & correlated noise*

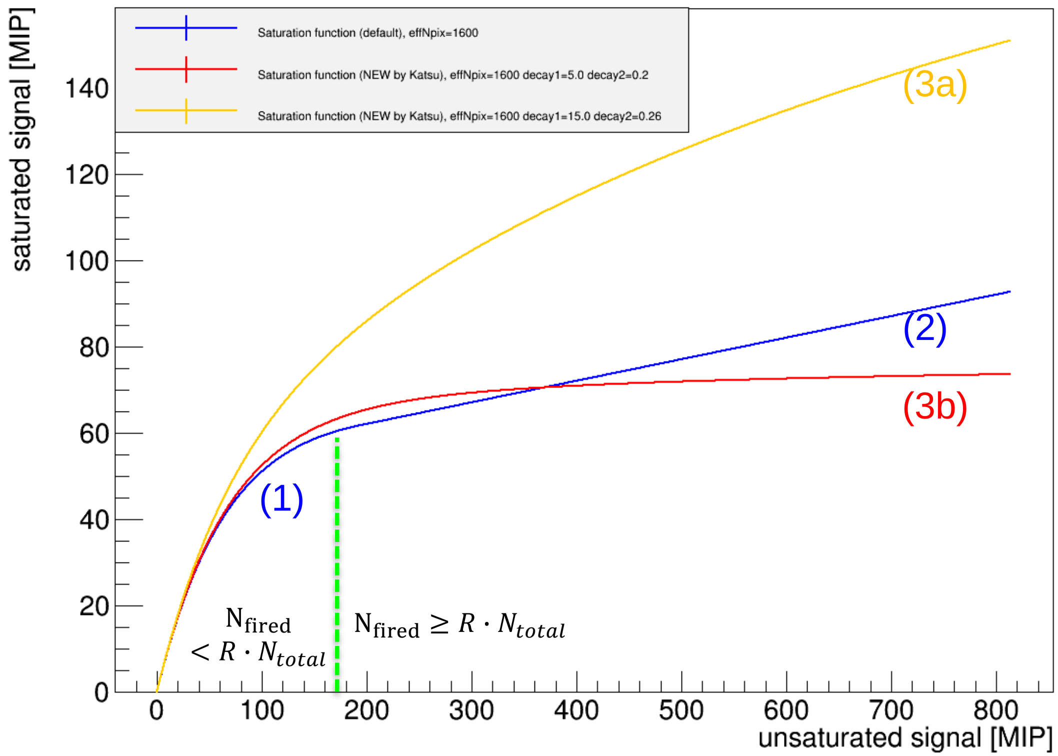




In calibration region:
influenced by correlated noise (XT):
$N_{fired} = N_{fired}^{linear} = \boldsymbol{N_{seed} \cdot \mu_C}$
$\Longrightarrow N_{seed} = N_{fired}^{linear} / \mu_C$
In this way, I_{ref} can be calibrated to N_{seed}

In saturation region:
Number of pixels fired influenced by saturation AND correlated noise (XT):
$N_{fired} = f(N_{seed})$

Describing saturation



No correlated noise covered:

Simple saturation function: (1)

$$N_{fired} = N_{total} \cdot \left(1 - exp\left(-\frac{N_{seed}}{N_{total}}\right)\right)$$

Linear extended saturation function used in CALICE to handle over saturation: (2)

If $N_{\text{fired}} \geq R \cdot N_{total}$, than:

$$N_{fired} = R \cdot N_{total} + (1 - R) \cdot \left(N_{seed} + N_{total} \cdot log(1 - R)\right)$$

for $R = 95\%$

Correlated noise covered:

Katsu's advanced SiPM function includes NLO corrections: (3a) (3b)

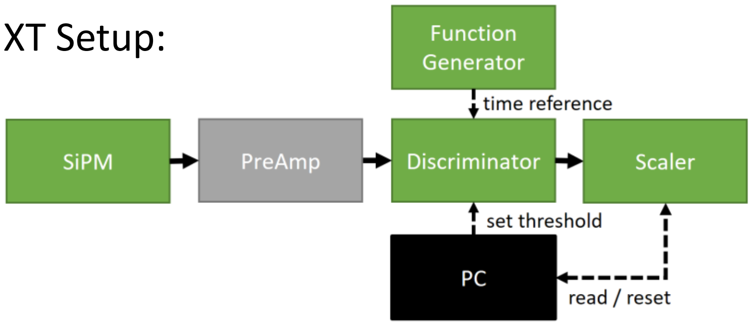
6 parameters:

- N_{total}, — fixed to total number of pixels
- scale factor, — fixed to 1
- 2x decay-/recovery time variables, — describes **over-saturation**
- Crosstalk- & Afterpulse prob. — includes **correlated noise**

Ref: K. Kotera: https://agenda.linearcollider.org/event/7304/contributions/37323/attachments/30512/45645/0g915SiPMfuncApplyingAHCAL2.pdf

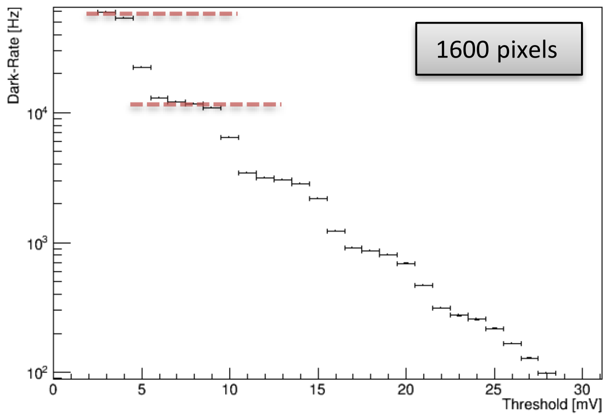
SiPM crosstalk (XT) measurement

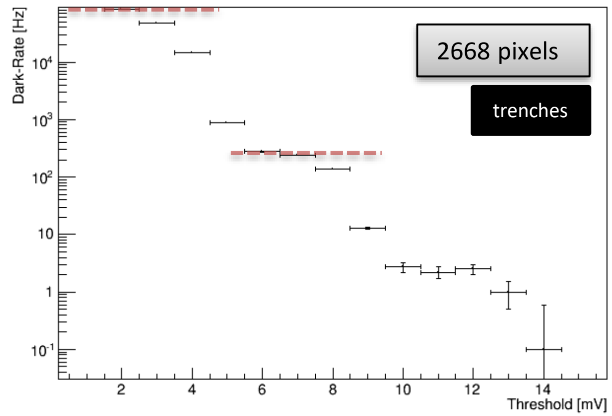
XT Setup:



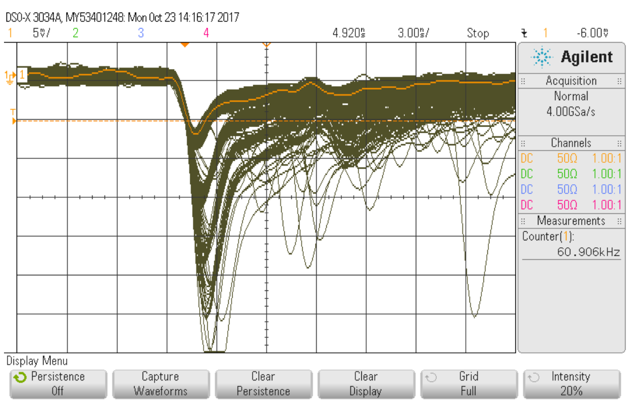
Under same conditions as during saturation measurements. Laser OFF.

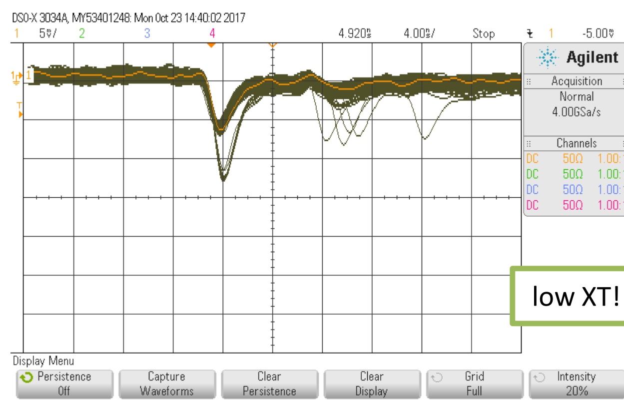
DCR:





Scope:





low XT!

Low amount of after pulses visible at every SiPM.

Factor of correlated pixels fired

To estimate the average number of correlated pixels fired, the **Borel Model of correlated noise** is used as described in detail in:
https://arxiv.org/pdf/1710.11410.pdf by Enrico Junior Schioppa

With:
N_0 = total number of events
N_1 = all events with exactly one pixel fired (no XT)
N_2 = events with exactly 1 XT (2 pixels fired in total)

Borel Model:

Equation to be solved: $\xi\left(e^{-\xi}-1\right)=\frac{N_2}{N_1}+\log\left(\frac{N_1}{N_0}\right)$

Expected value: $\mu=\frac{1}{1-\xi}$

arXiv:1710.11410v1

SiPM MPPC	N_{total}	$P(\geq 1\ XT)$	N_0	N_1	N_2	ξ	μ
S13360 -1325PE	2668	0.55%	46778.9 (100%)	46523.8 (99.45%)	252.7 (0.54%)	$6.1768 \cdot 10^-3$	1.0062
S12571 -25P	1600	20.19%	59229.6 (100%)	47269.1 (79.81%)	8964.0 (15.13%)	0.19905	1.2485
S12571 -50P	400	28.01%	99891.1 (100%)	71915.8 (71.99%)	17374.4 (17.39%)	0.31873	1.4679
S12571 -100P	100	38.19%	71284.8 (100%)	44059.6 (61.81%)	13420.2 (18.83%)	0.47045	1.8884

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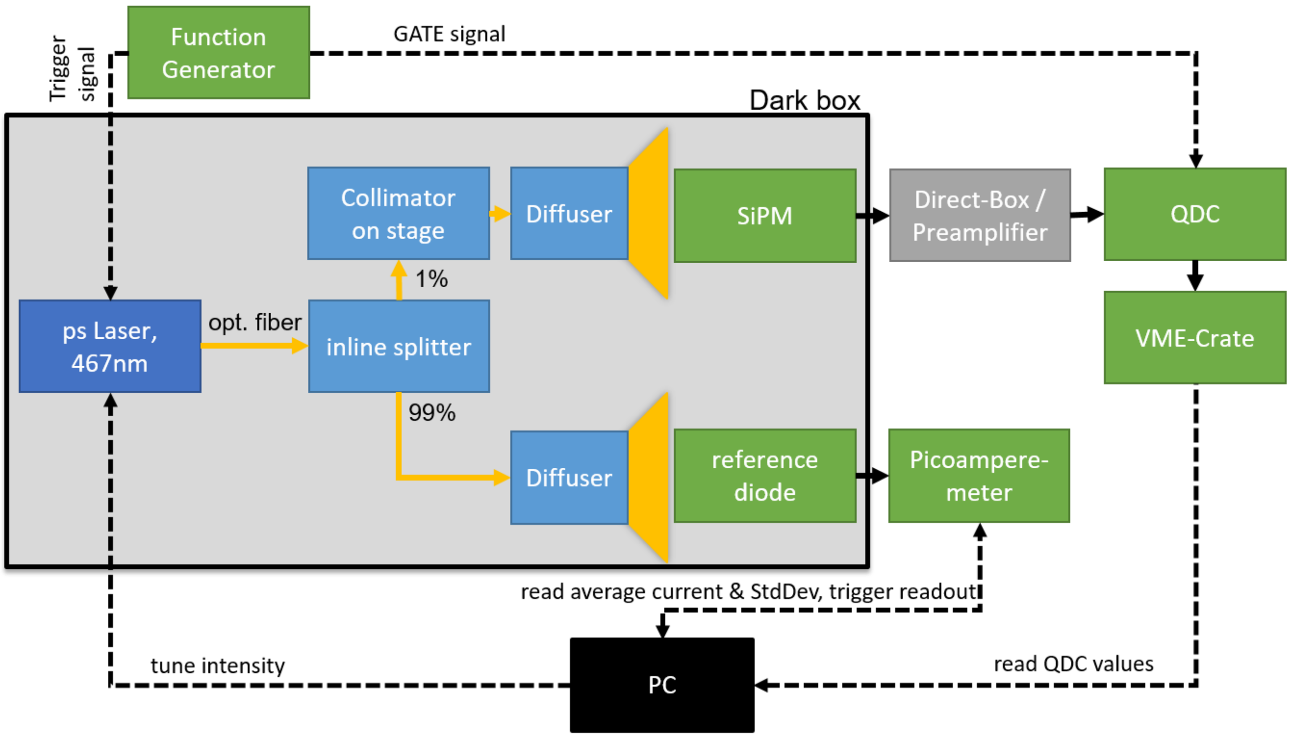
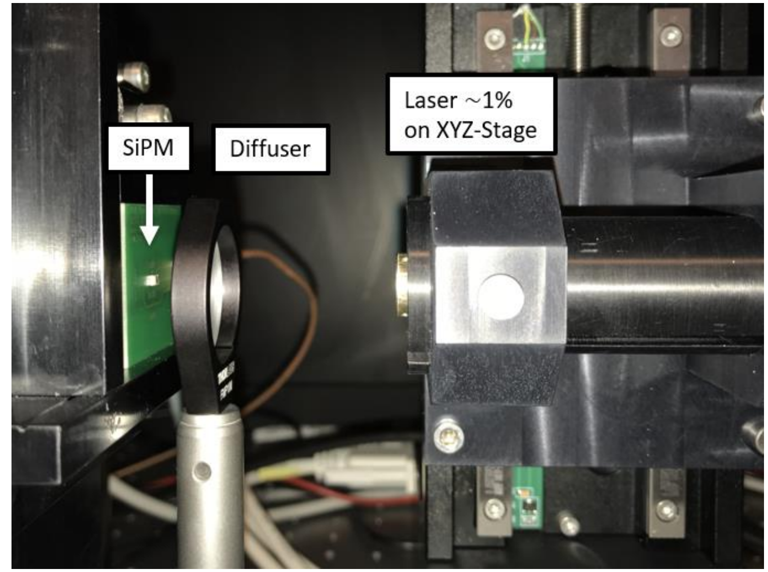
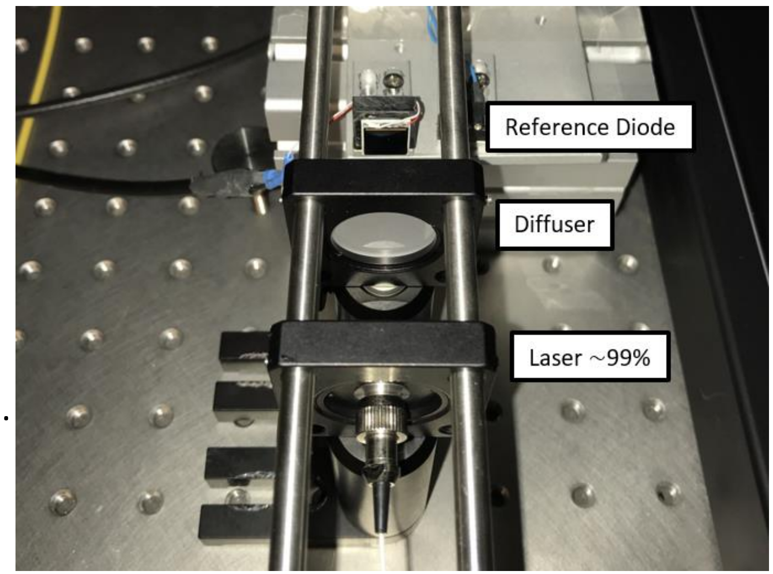
SiPM Saturation: Setup







<u>Linearity secured:</u>

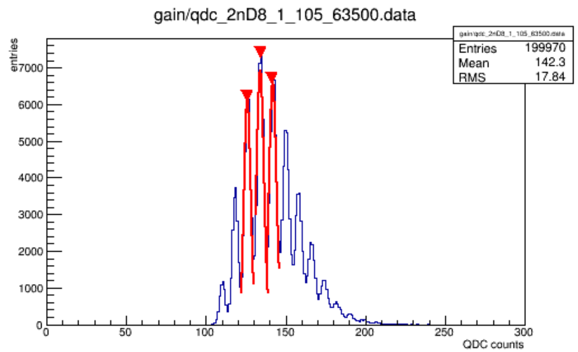
- Direct-Readout-Circuit linear within 1% over full measurement range.
- PreAmp starts to saturate from ~1V output, linear within 1-2% for lower signals.
- Reference diode linear within 1% over full measurement range.

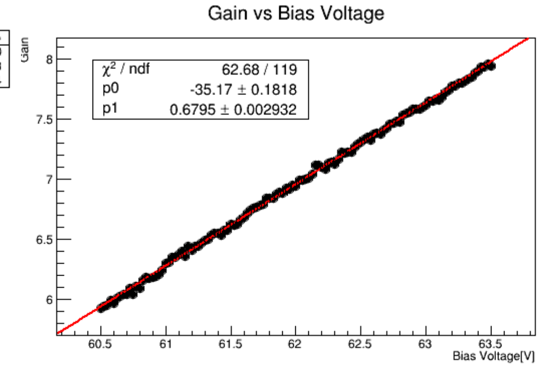
<u>Uniform light distribution:</u>

- Diffusor scan performed.

SiPM Saturation: Procedure for latest SiPM (2668 pixels)

1. Pedestal correction:
QDC Spectrum with applied bias voltage without laser beam. Used for pedestal determination.

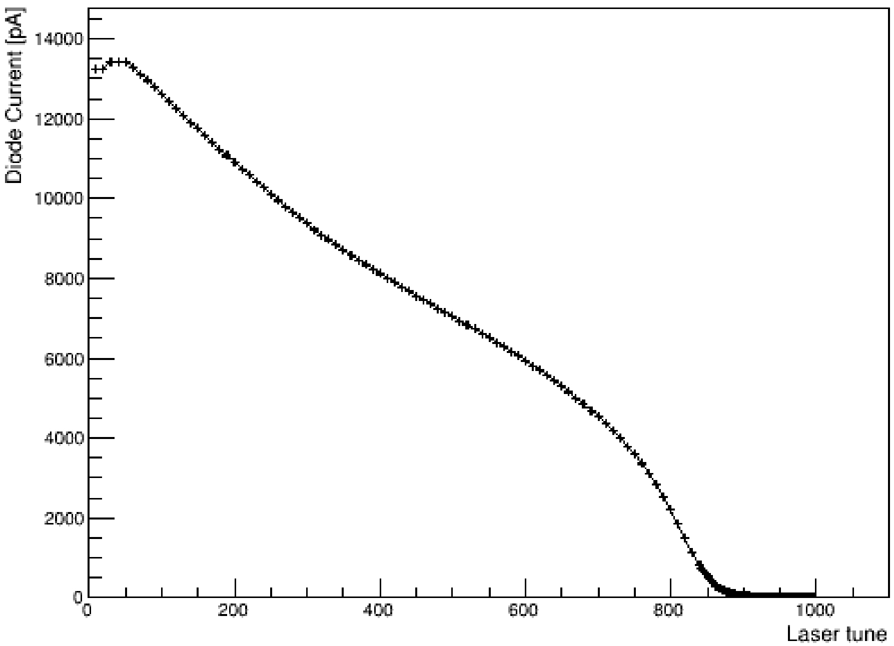




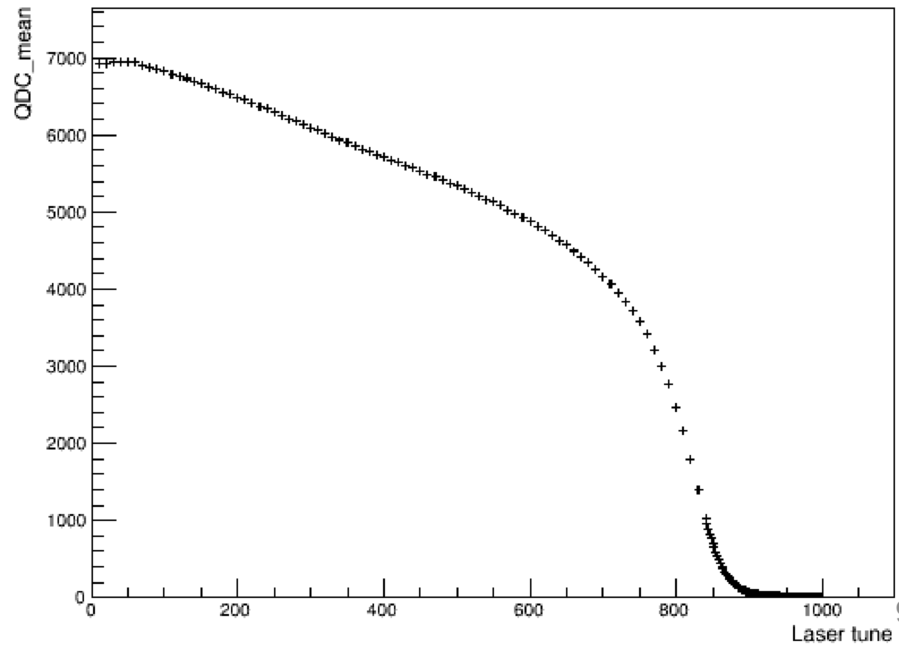
2. Gain measurement:
Difference between adjacent peaks.
In case of 1600 pixel SiPM: use Preamp and Direct Box.

3. High Range to Low Range conversion:
The QDC has a LR and HR amplification. Measure conversion factor.

4. Estimate light intensity with calibrated diode:



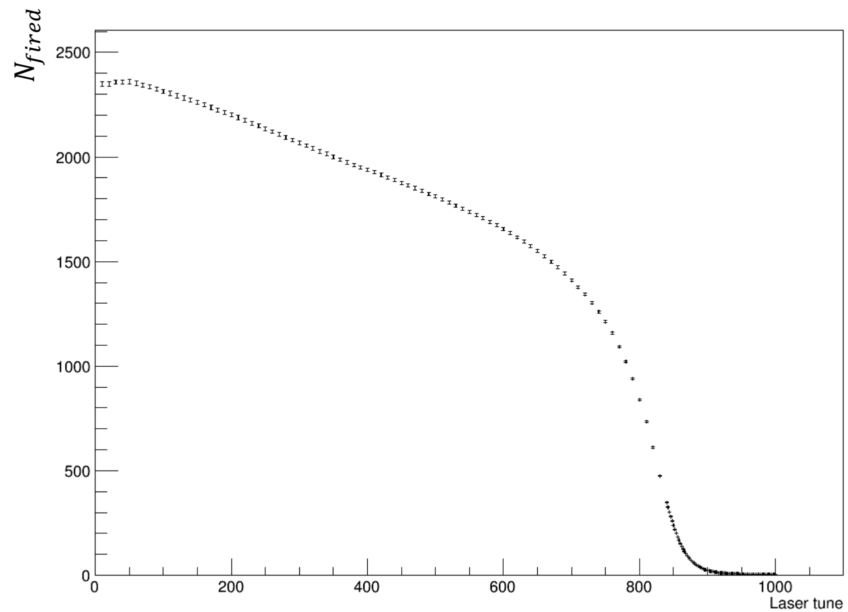
5. Plot QDC mean values vs. laser intensity:



SiPM Saturation: Procedure for latest SiPM (2668 pixels)

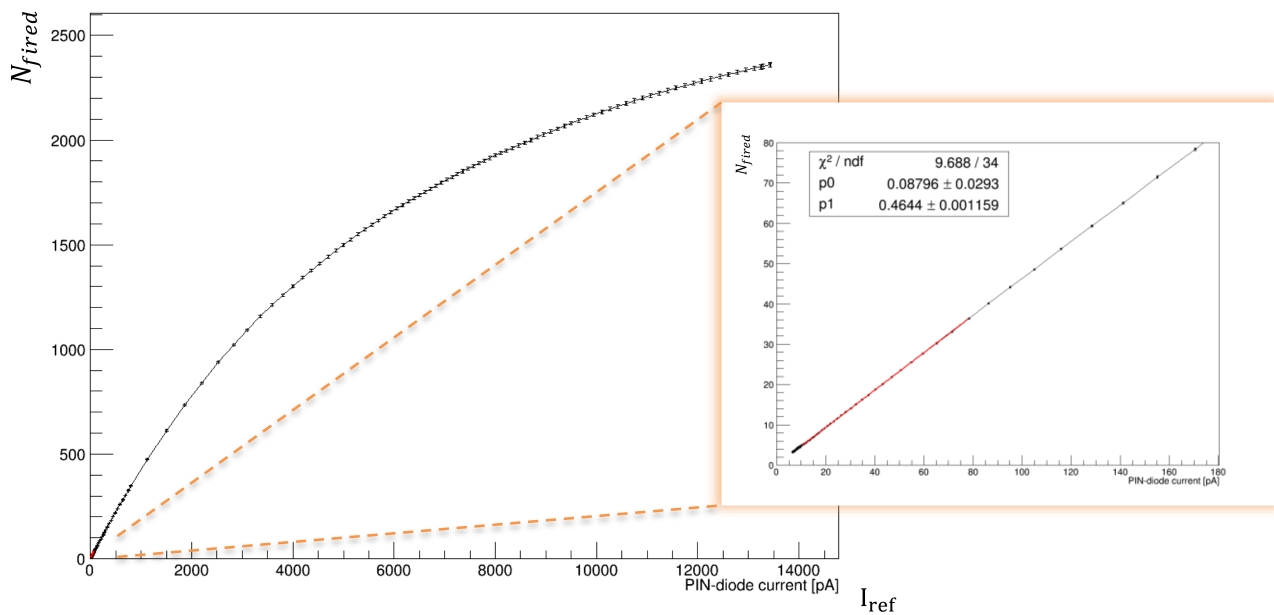
6. Estimate and plot N_{fired} vs Laser Tune:

$$N_{fired} = (QDC_{mean} - pedestal)/gain$$



7. Plot #pixels vs Diode Current.

8. Apply linear Fit to first measurement points, where linear behavior is still expected:
Determine number of "**Seeds**", N_{seed}!



In calibration region:

Definition of N_{fired}^{linear}:

$$N_{fired}^{linear}(i) = p0 + p1 \cdot I_{ref}(i)$$

Definition of N_{seed}:

$$N_{seed}(i) = N_{fired}^{linear}(i)/\mu_C$$

$\Longrightarrow$ convert reference current to number of seeds.

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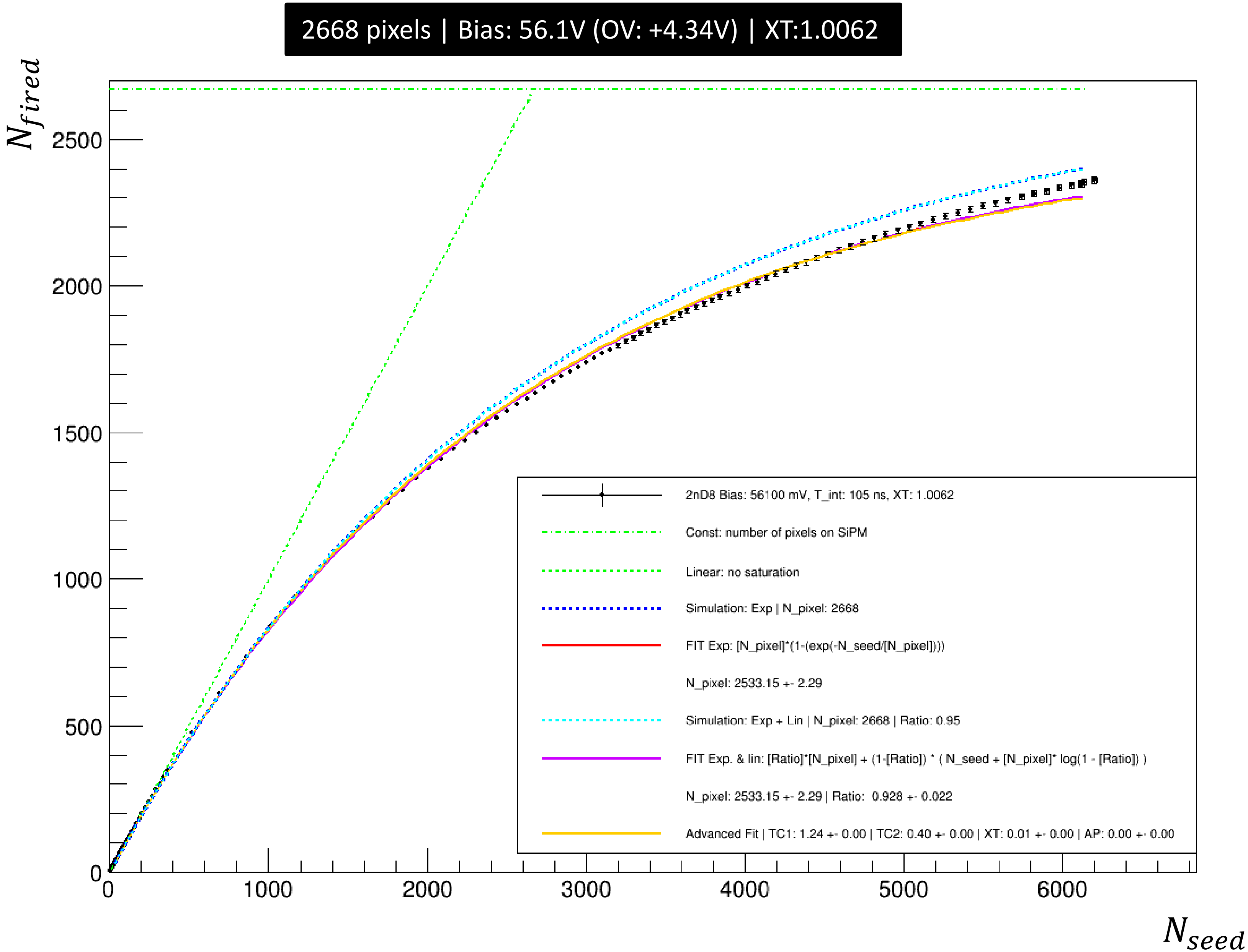
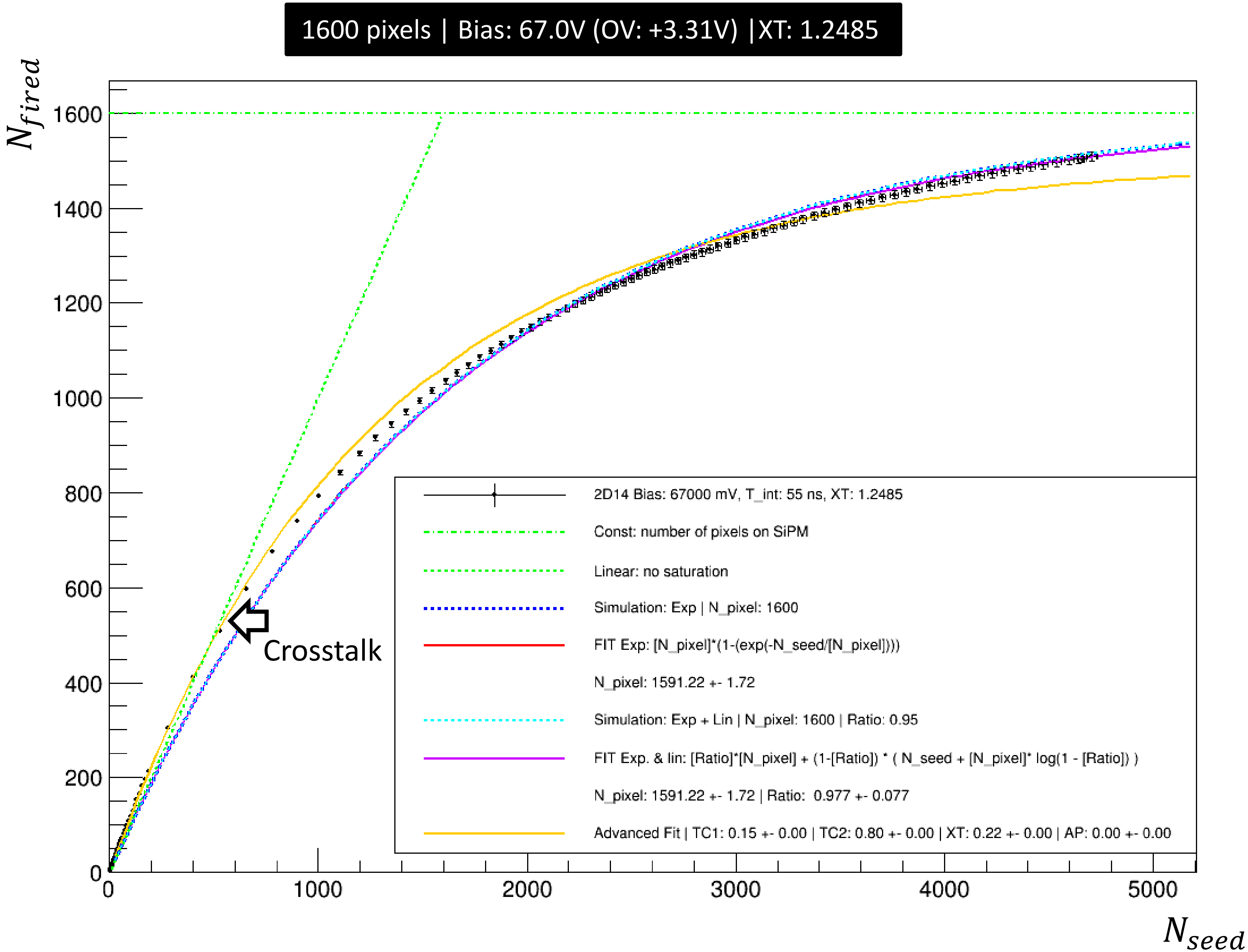
Results

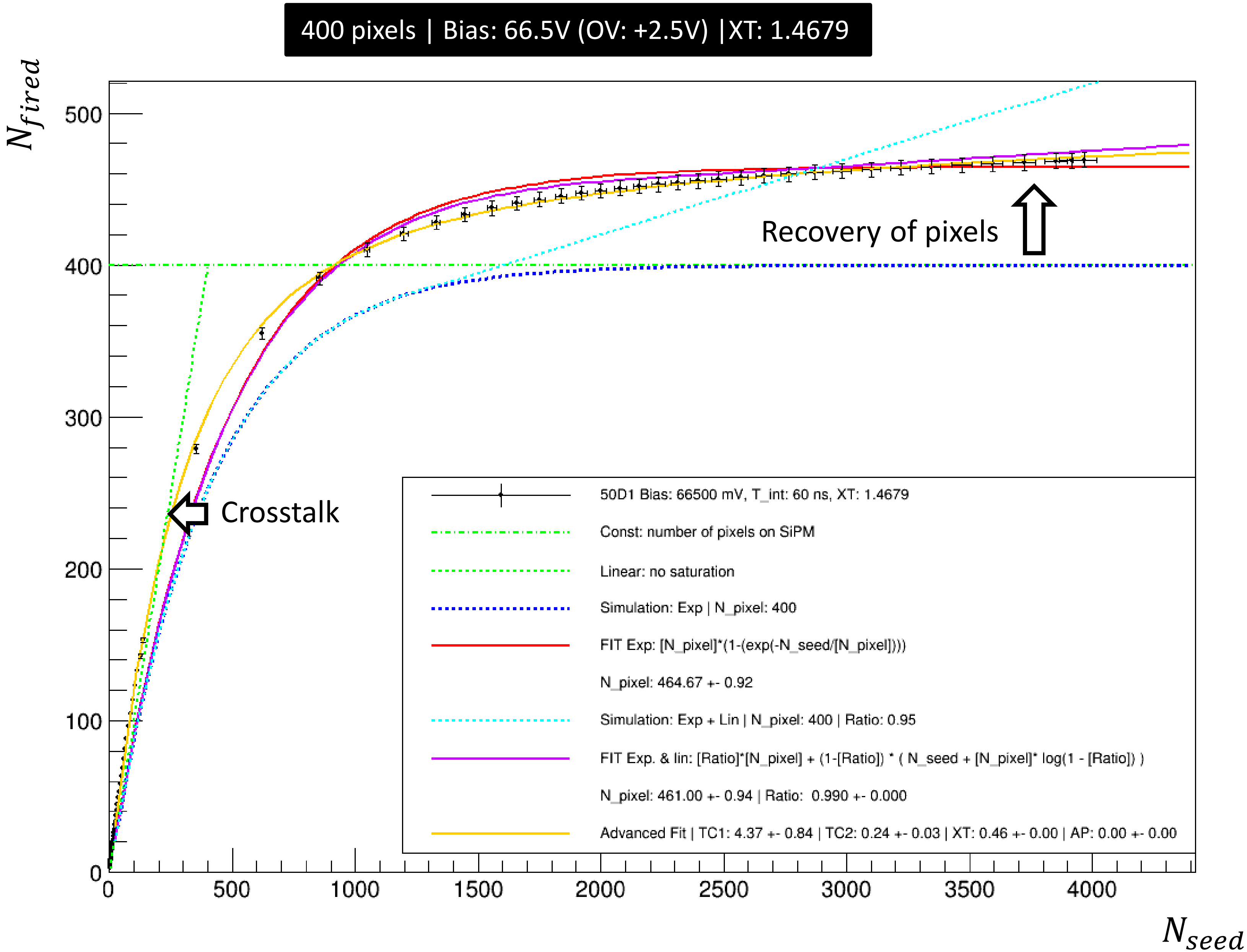


2668 pixels | Bias: 56.1V (OV: +4.34V) | XT:1.0062
N_{fired}
2500
2000
1500
1000
500
0
0
1000
2000
3000
4000
5000
6000
N_{seed}
2nD8 Bias: 56100 mV, T_int: 105 ns, XT: 1.0062
Const: number of pixels on SiPM
Linear: no saturation
Simulation: Exp | N_pixel: 2668
FIT Exp: [N_pixel]*(1-(exp(-N_seed/[N_pixel])))
N_pixel: 2533.15 +- 2.29
Simulation: Exp + Lin | N_pixel: 2668 | Ratio: 0.95
FIT Exp. & lin: [Ratio]*[N_pixel] + (1-[Ratio]) * (N_seed + [N_pixel]* log(1 - [Ratio]))
N_pixel: 2533.15 +- 2.29 | Ratio: 0.928 +- 0.022
Advanced Fit | TC1: 1.24 +- 0.00 | TC2: 0.40 +- 0.00 | XT: 0.01 +- 0.00 | AP: 0.00 +- 0.00

Results

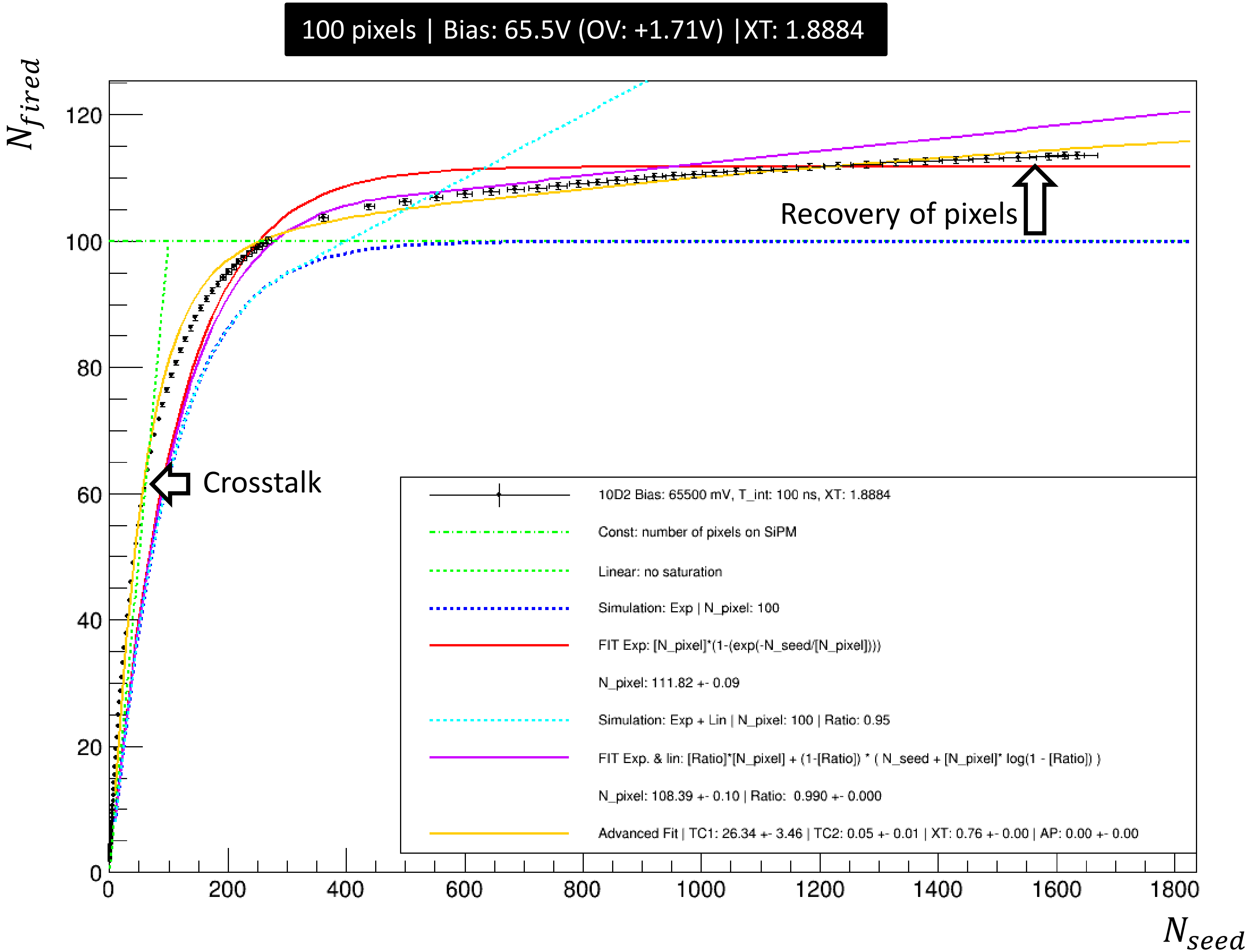

1600 pixels | Bias: 67.0V (OV: +3.31V) |XT: 1.2485
N_{fired}
N_{seed}
Crosstalk
2D14 Bias: 67000 mV, T_int: 55 ns, XT: 1.2485
Const: number of pixels on SiPM
Linear: no saturation
Simulation: Exp | N_pixel: 1600
FIT Exp: [N_pixel]*(1-(exp(-N_seed/[N_pixel])))
N_pixel: 1591.22 +- 1.72
Simulation: Exp + Lin | N_pixel: 1600 | Ratio: 0.95
FIT Exp. & lin: [Ratio]*[N_pixel] + (1-[Ratio]) * (N_seed + [N_pixel]* log(1 - [Ratio]))
N_pixel: 1591.22 +- 1.72 | Ratio: 0.977 +- 0.077
Advanced Fit | TC1: 0.15 +- 0.00 | TC2: 0.80 +- 0.00 | XT: 0.22 +- 0.00 | AP: 0.00 +- 0.00

Results



400 pixels | Bias: 66.5V (OV: +2.5V) |XT: 1.4679
N_{fired}
500
400
300
200
100
0
0
500
1000
1500
2000
2500
3000
3500
4000
N_{seed}
Recovery of pixels
Crosstalk
50D1 Bias: 66500 mV, T_int: 60 ns, XT: 1.4679
Const: number of pixels on SiPM
Linear: no saturation
Simulation: Exp | N_pixel: 400
FIT Exp: [N_pixel]*(1-(exp(-N_seed/[N_pixel])))
N_pixel: 464.67 +- 0.92
Simulation: Exp + Lin | N_pixel: 400 | Ratio: 0.95
FIT Exp. & lin: [Ratio]*[N_pixel] + (1-[Ratio]) * (N_seed + [N_pixel]* log(1 - [Ratio]))
N_pixel: 461.00 +- 0.94 | Ratio: 0.990 +- 0.000
Advanced Fit | TC1: 4.37 +- 0.84 | TC2: 0.24 +- 0.03 | XT: 0.46 +- 0.00 | AP: 0.00 +- 0.00

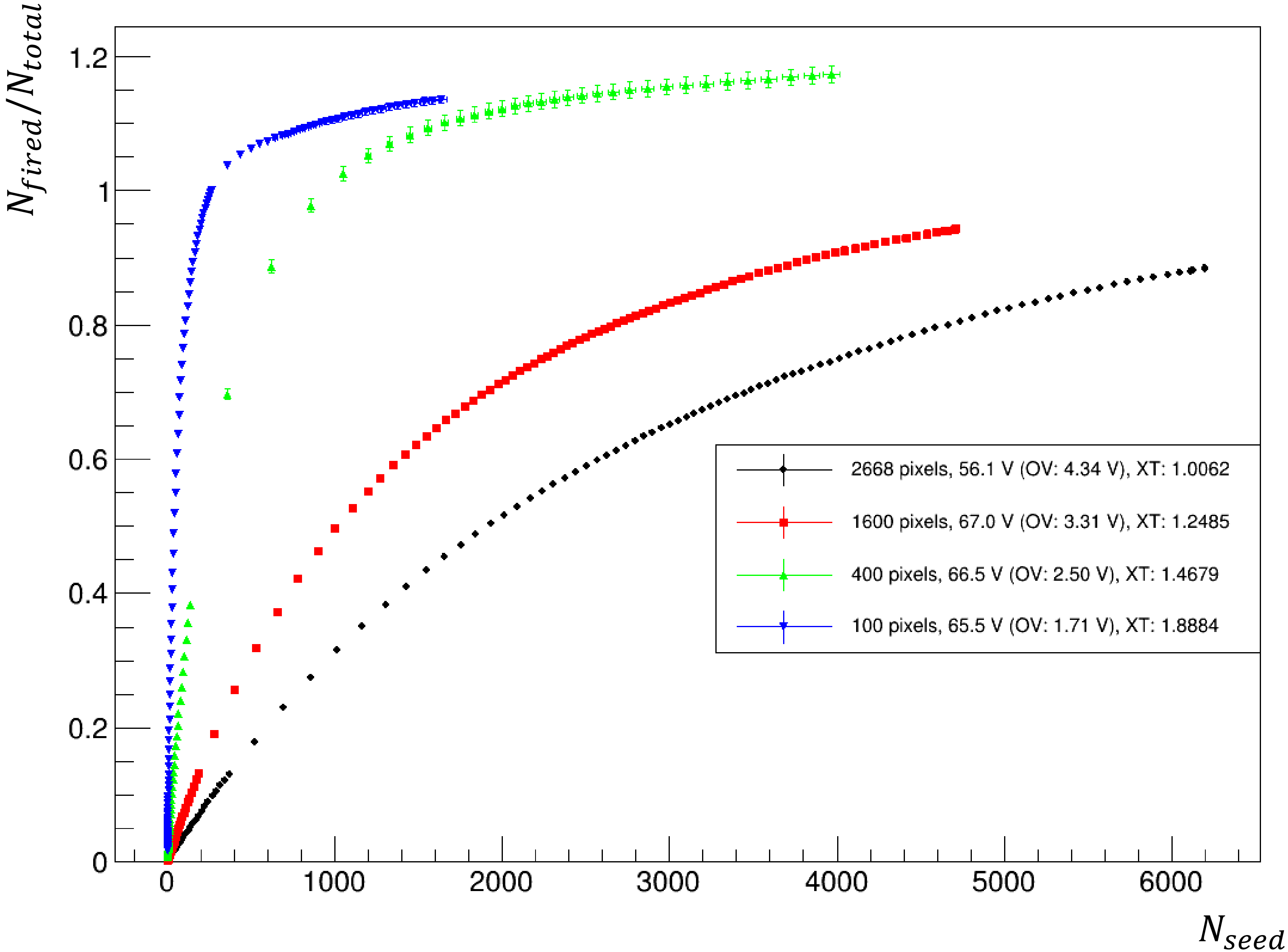
Results



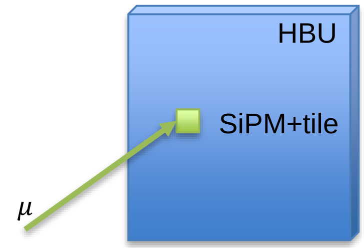
100 pixels | Bias: 65.5V (OV: +1.71V) |XT: 1.8884
N_{fired}
120
100
80
60
40
20
0
0
200
400
600
800
1000
1200
1400
1600
1800
N_{seed}
Recovery of pixels
Crosstalk
10D2 Bias: 65500 mV, T_int: 100 ns, XT: 1.8884
Const: number of pixels on SiPM
Linear: no saturation
Simulation: Exp | N_pixel: 100
FIT Exp: [N_pixel]*(1-(exp(-N_seed/[N_pixel])))
N_pixel: 111.82 +- 0.09
Simulation: Exp + Lin | N_pixel: 100 | Ratio: 0.95
FIT Exp. & lin: [Ratio]*[N_pixel] + (1-[Ratio]) * (N_seed + [N_pixel]* log(1 - [Ratio]))
N_pixel: 108.39 +- 0.10 | Ratio: 0.990 +- 0.000
Advanced Fit | TC1: 26.34 +- 3.46 | TC2: 0.05 +- 0.01 | XT: 0.76 +- 0.00 | AP: 0.00 +- 0.00

Combined Saturation Measurement Results

relative scale



Implementation in CALICE ?



Default Digitization process:

Crosstalk effect not handled at all:

- LY-calibration is also crosstalk affected!

Ahc2MIP2GeVProcessor: Convert MC energies from GeV to MIP, using a GeV->MIP factor from simulation.

Ahc2ROCThresholdProcessor: Add sub hits, apply 0.5MIP threshold.

Ahc2SiPMStatisticsProcessor:

- MIP -> #pixels: $N_{seed} = E_{MIP}^{MC} \cdot \boldsymbol{LY}$
- Saturate using exp. function: $N_{fired}^{*} = f^{exp}(N_{seed})$
- Binomial smearing $N_{fired} = smear(N_{fired}^{*}, N_{total})$
- #pixels -> ADC: $ADC = N_{fired} \cdot gain$

If we want to use Katsu's advanced SiPM function, we have to use a LY-calibration which is corrected for correlated noise:

$$LY_{seed} = \frac{LY}{\mu_C}$$

In reconstruction:

ADC is converted to Pixels, de-saturated and converted to MIP.

Prediction:

For low number of MIPs, the difference should be small, since the XT is constant and the saturation effect low.

For rising number of MIPs, the crosstalk effect will get smaller, since there are less non-hit pixels on the SiPM. Since the LY is enlarged by a constant XT, the digitized Energy will be higher than it actually is in the default mode. The advanced function with XT corrected LY can handle this effect.

For large number of MIPs, an over-saturation can be described with the advanced function.

Conclusion

For 4 different SiPM:

Crosstalk measurement performed: μ_C

Saturation measurement:

100 and 400 pixel SiPM:

- *Crosstalk* has a large influence.
- For high light intensities, an over-saturation has been observed.

1600 and 2668 pixel SiPM:

- Since the crosstalk prob. is lower (and in case of 2668pix negligible), it has a lower, but measurable influence.
- The light intensity (& low ε_{PDE}) is too low to reach the region of over-saturation.
- In the case of low crosstalk SiPMs, the simple exponential saturation function shows a good agreement to data in the high light region, while Katsu's advanced function rebuilds the low light region in a better way.

Next steps:

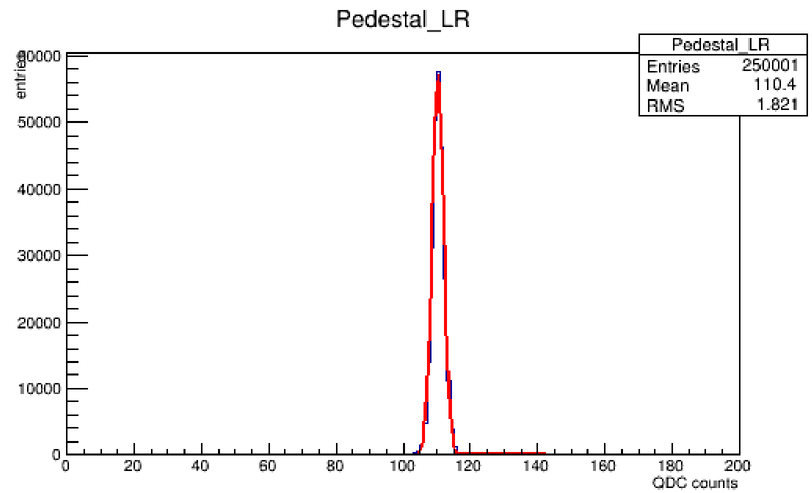
- Implementation in CALICE MC digitization and data reconstruction planed.
- Combined SiPM+tile measurement with UV Laser

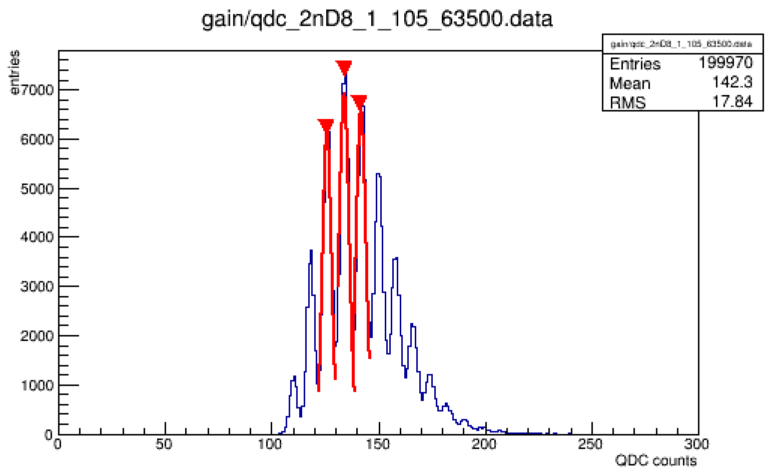
Questions? ☺

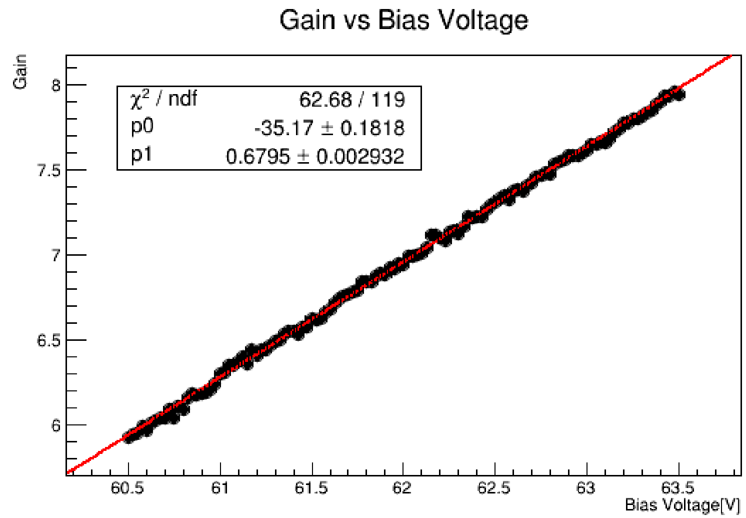
SiPM Saturation: Procedure for latest SiPM (2668 pixels)

<u>1. Pedestal correction:</u>
QDC Spectrum with applied bias voltage without laser beam. Used for pedestal determination.

<u>2. Gain measurement:</u>
Difference between adjacent peaks.



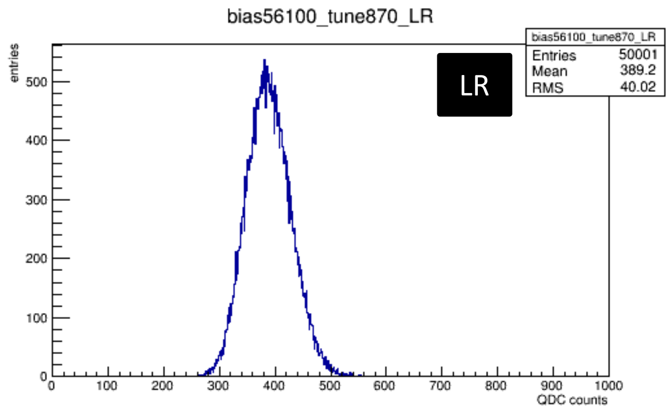


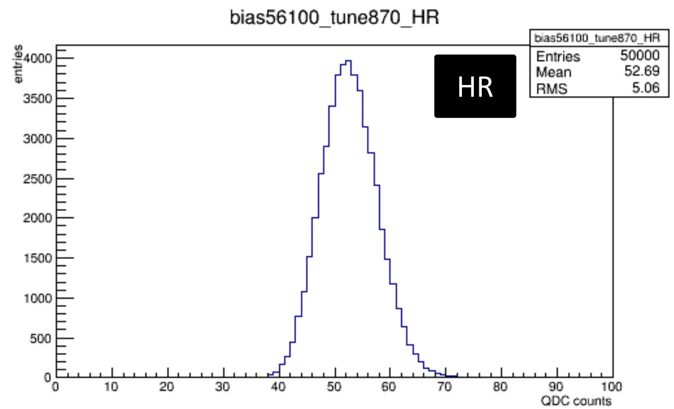


SiPM Saturation: Procedure for latest SiPM (2668 pixels)

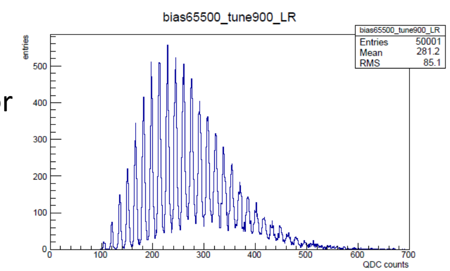
<u>3. High Range to Low Range conversion:</u>
The QDC has a LR and HR amplification.

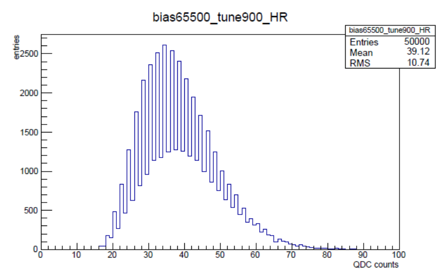
Same events with QDC LR (left) and HR (right) amplification.



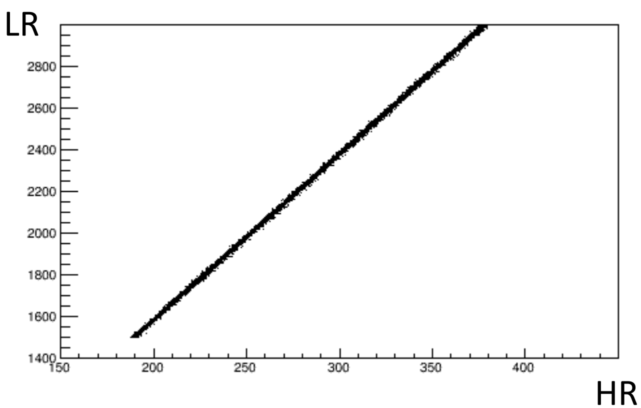


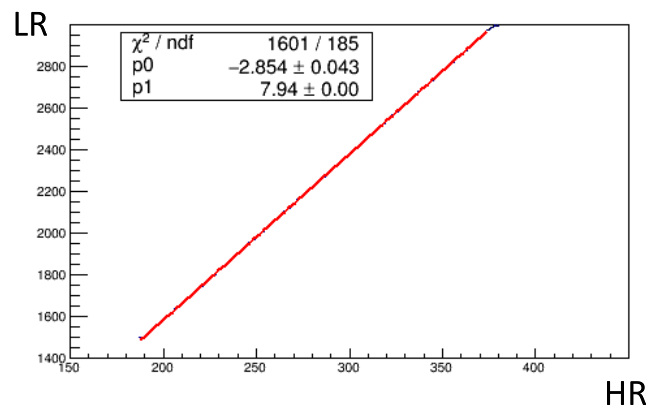
How it looks like for a 100 pixel SiPM with higher gain:





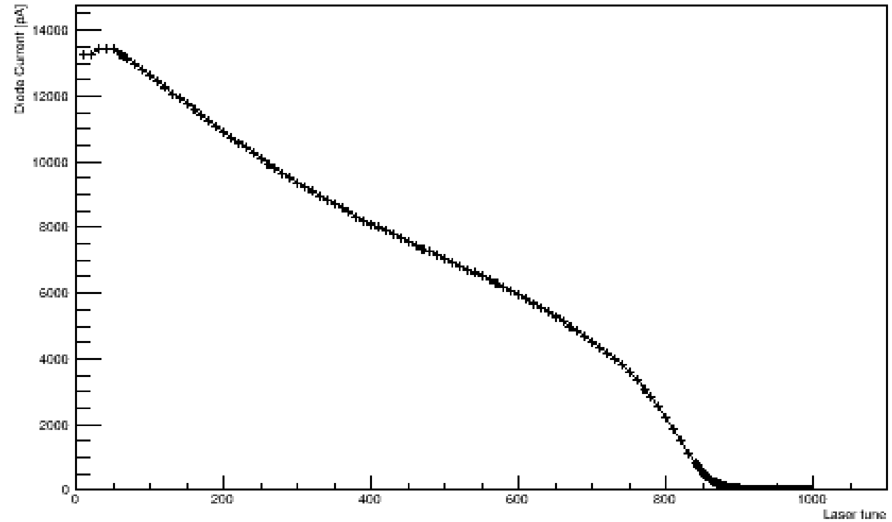
LR vs. HR.
Fit used for conversion.



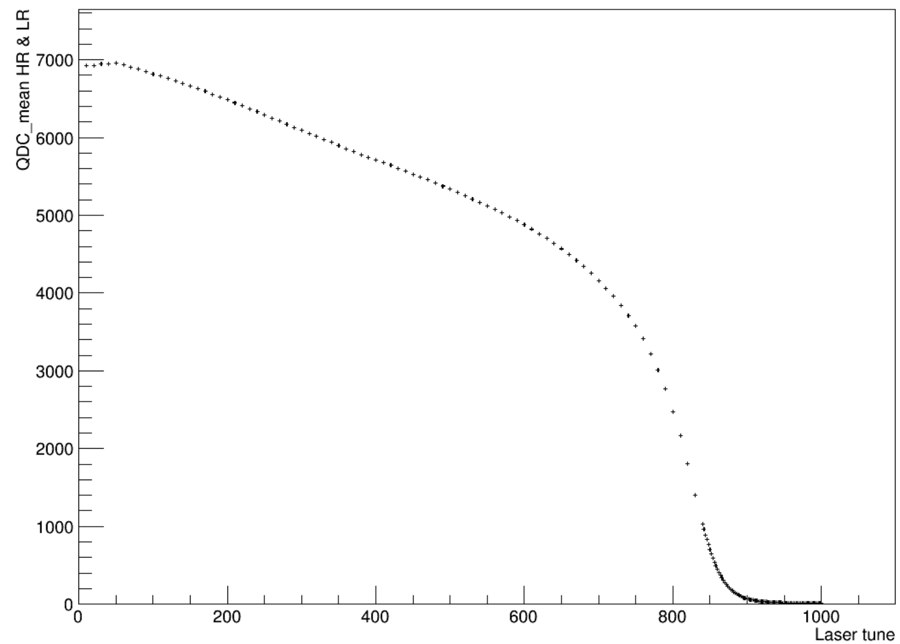


SiPM Saturation: Procedure for latest SiPM (2668 pixels)

4. Estimate light intensity with calibrated diode:

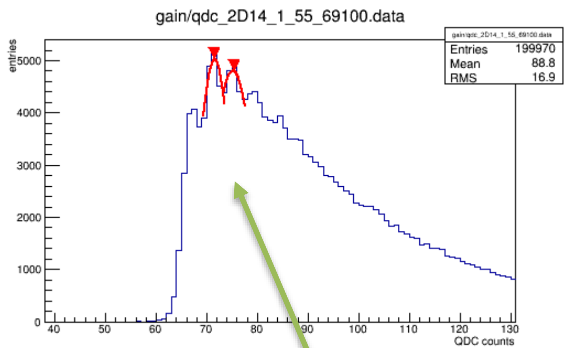


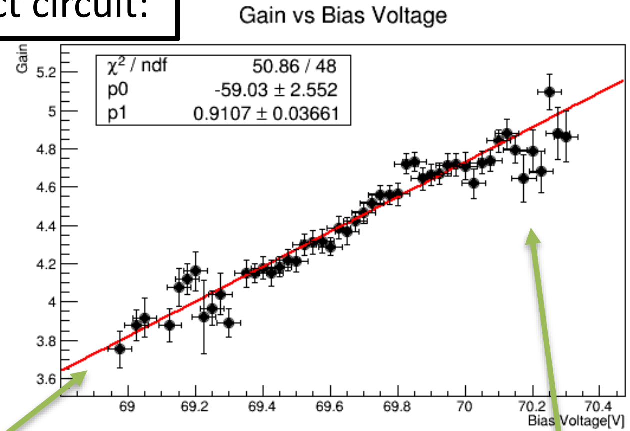
5. Plot QDC mean values vs. laser intensity:

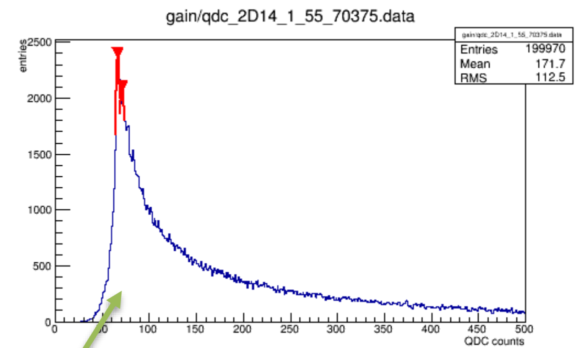


Need for Preamplifier for 1600pix SiPM

No gain measurement possible with direct circuit:







Too low bins to get precise information.

Gain measurement hard to judge. High noise (AP) affects SPS -> Peakfinder suffers:

Use preamplifier:

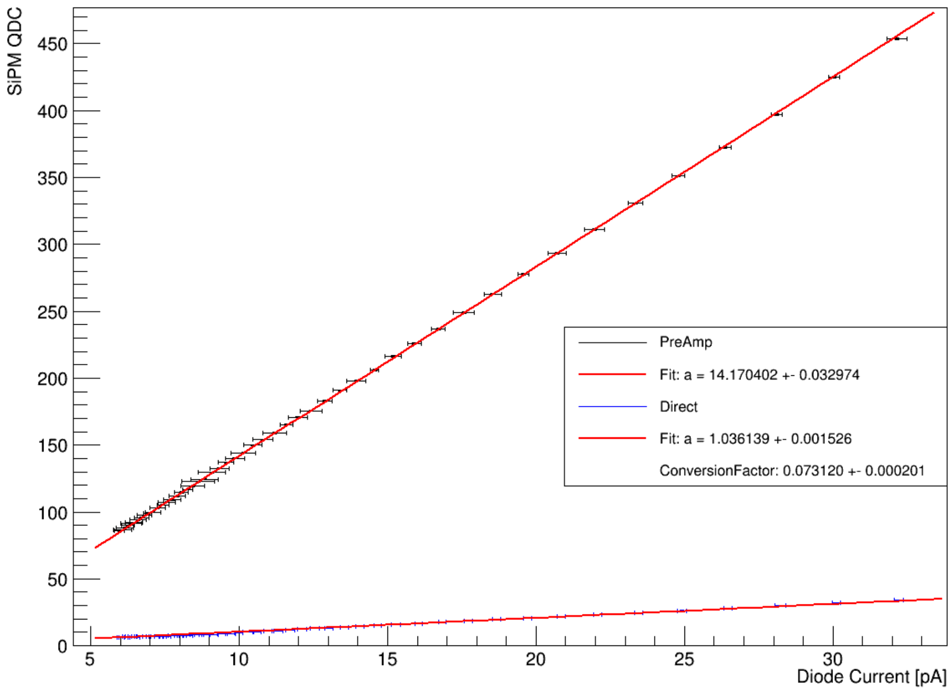
Issue: PreAmp is only linear in a known range.

Plan: Measure saturation twice without changing optics:

1. with DirectBox
2. with PreAmp in linear range

Gain Estimation with PreAmp | Conversion factor: PreAmp -> DirectBox

Plot QDC values vs. diode current
Apply linear fits:



Conversion Factor:

$$\alpha = \frac{f_D}{f_P} = \frac{a_D}{a_P} = 0.073120 \pm 0{,}000201$$

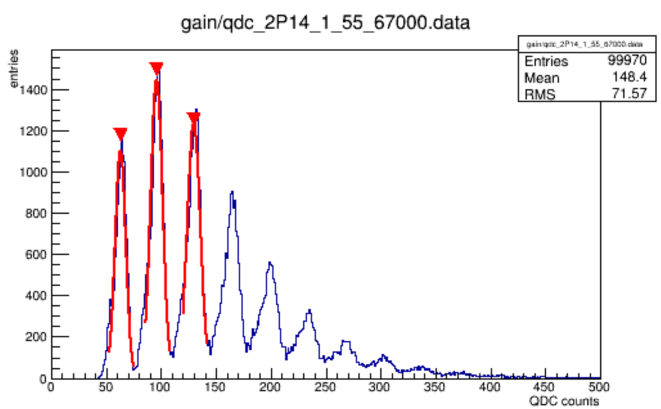
With this factor, the gain value can be estimated:
gain_PreAmp = 33.61
-> gain_Direct = 2,457 +-0,015

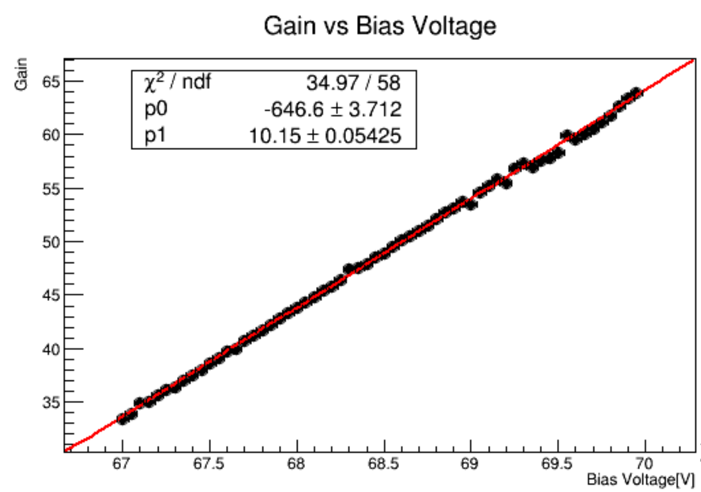
$$\Delta\alpha = \sqrt{\left(\frac{\Delta a_D}{a_P}\right)^2 + \left(-\frac{a_D \cdot \Delta a_P}{a_P^2}\right)^2}$$

$$gain_D = \alpha \cdot gain_P$$

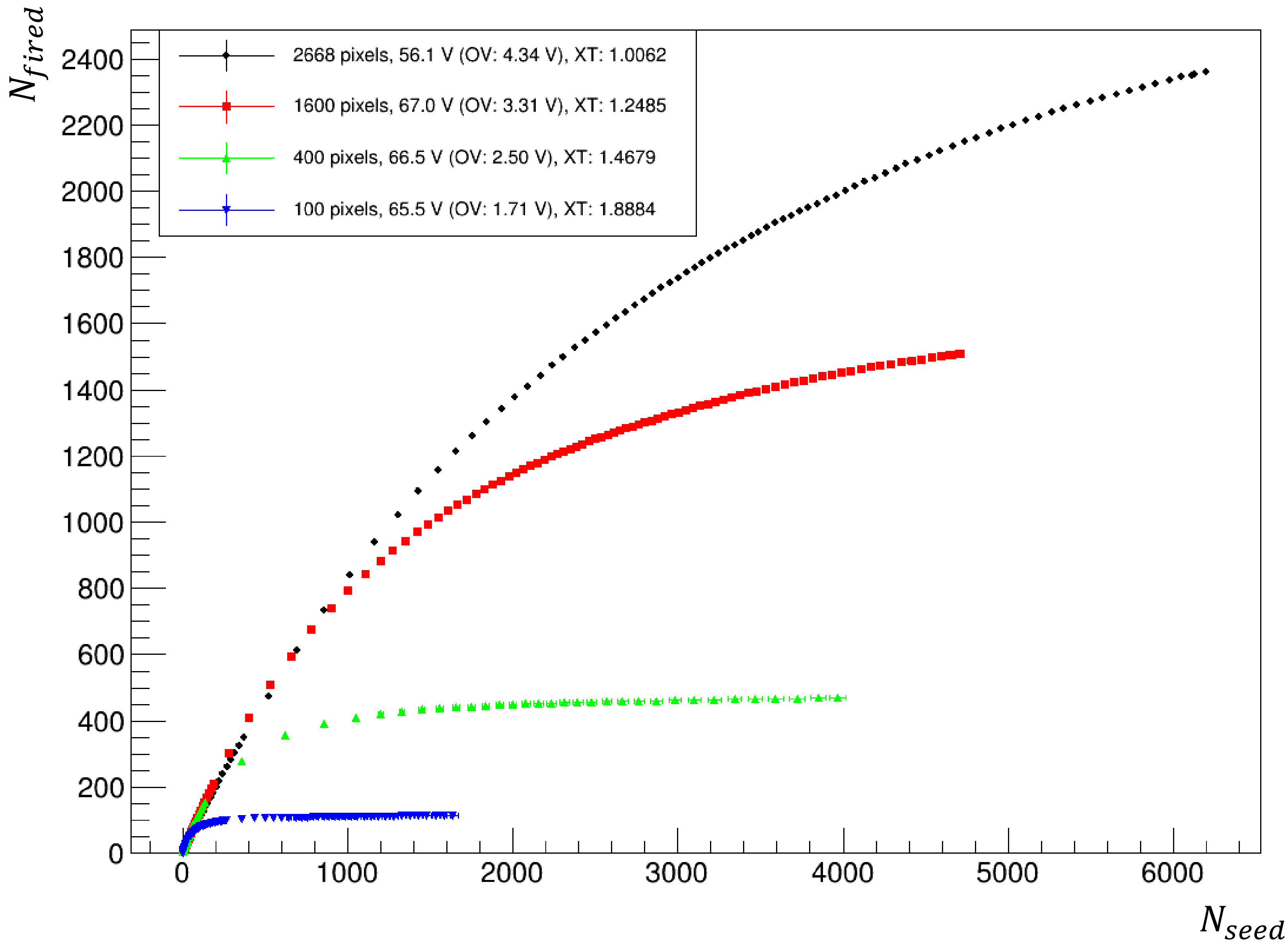
$$\Delta gain_D = \sqrt{(\Delta\alpha \cdot gain_P)^2 + (\alpha \cdot \Delta gain_P)^2}$$

Gain Measurement with PreAmp:

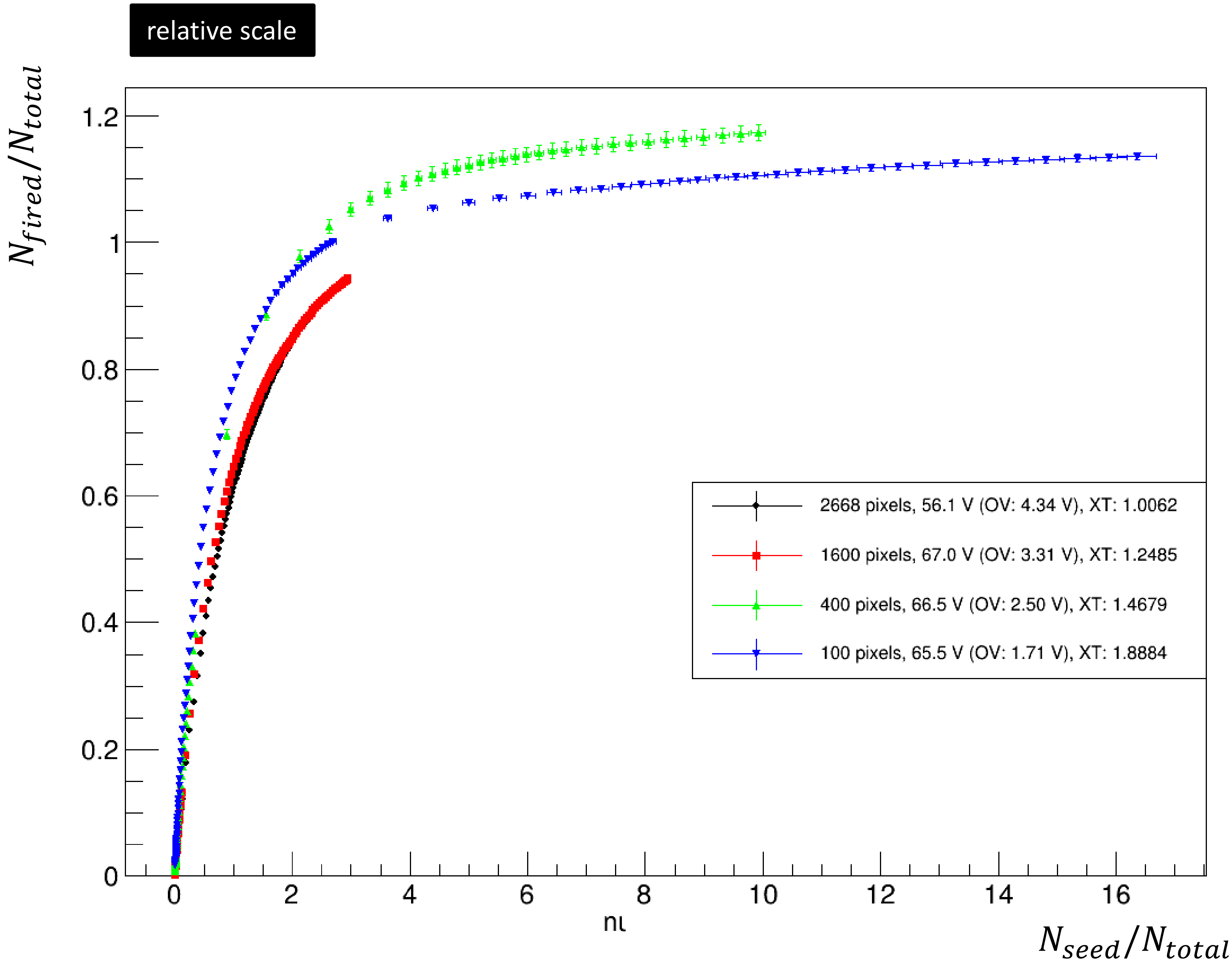




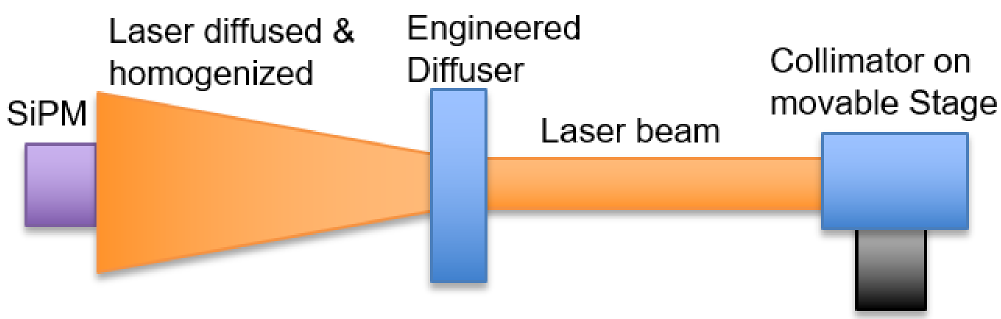
Combined Saturation Measurement Results

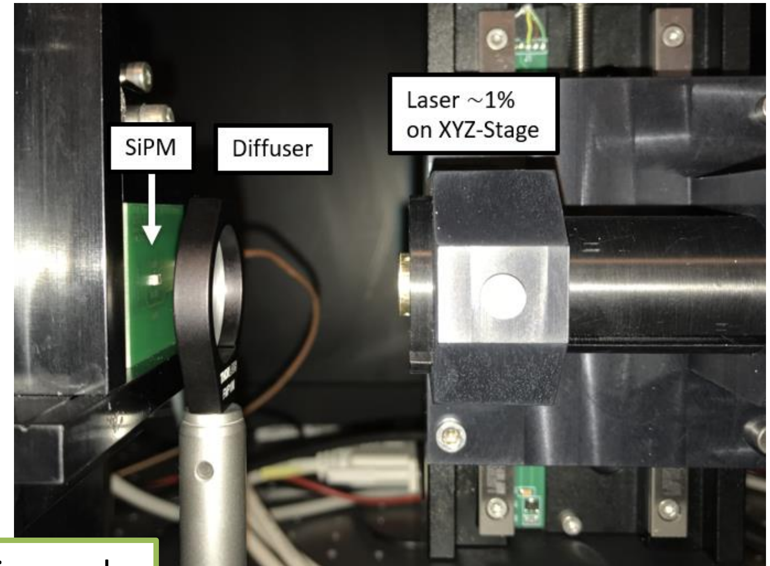


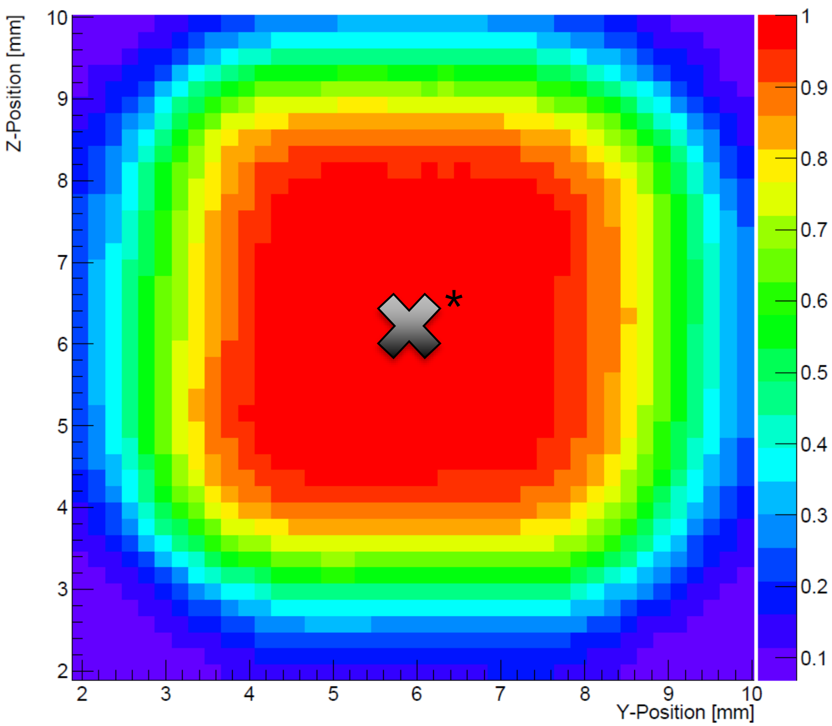
Combined Saturation Measurement Results



Engineered Diffuser Scan







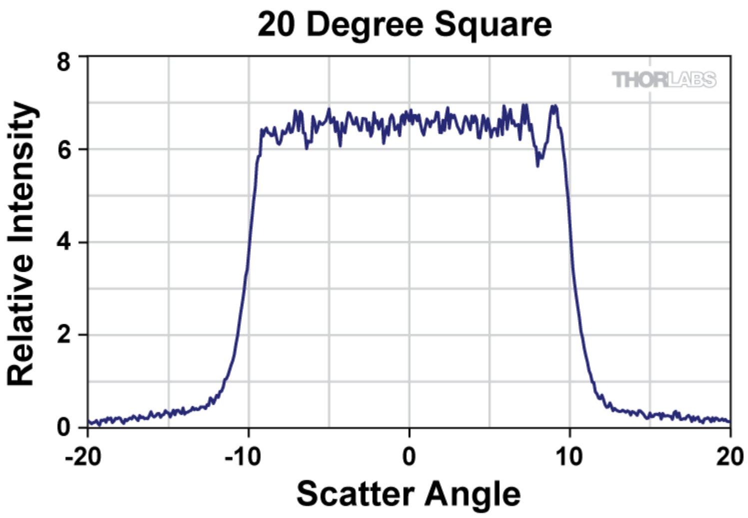
The uniformity of the Engineered Diffuser was tested in a separate measurement. It converts a gaussian beam profile in a so-called top-hat profile with uniform intensity.

Measured with 1600pix SiPM with 1x1mm² active surface.
The red area indicates a very uniform illumination of the SiPM.
The green halo corresponds to the cases, where only parts of the SiPM are hit.

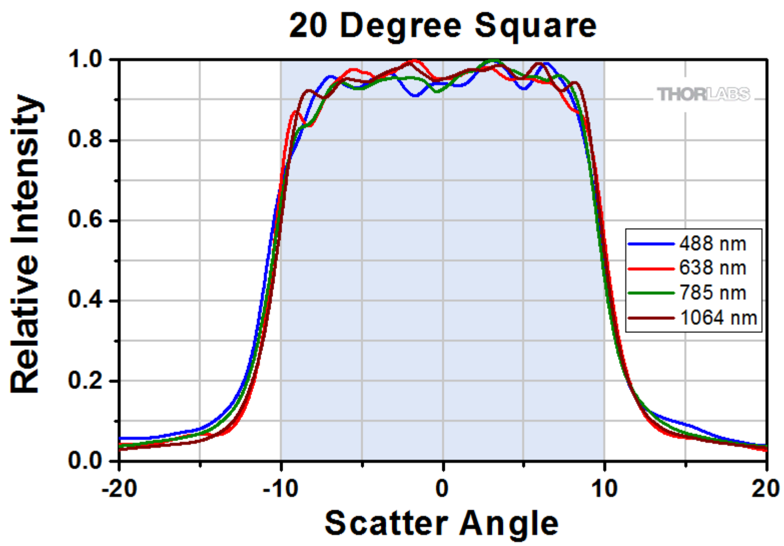
*Position used during saturation measurement.

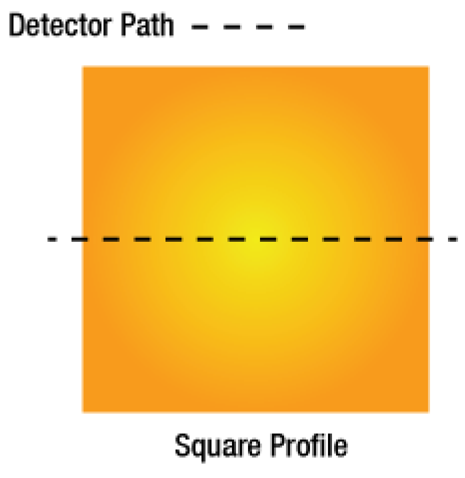
Diffusor: Thorlabs provided data

Thorlabs:
Theoretical Data



Thorlabs:
Measured Data





Katsu's advanced SiPM function

Katsu's advanced SiPM function includes NLO corrections:

6 parameters:

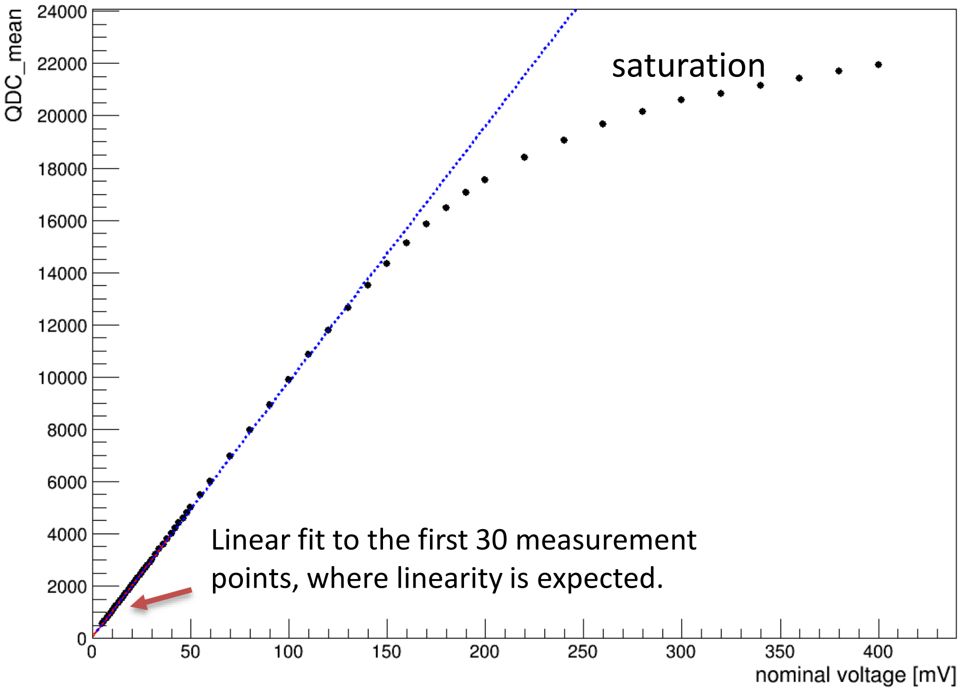
- #pixels, fixed to real number of pixels
- scale factor, fixed to 1
- 2x decay-/recovery time variables, describe over-saturation
- Crosstalk- & Afterpulse prob. includes correlated noise

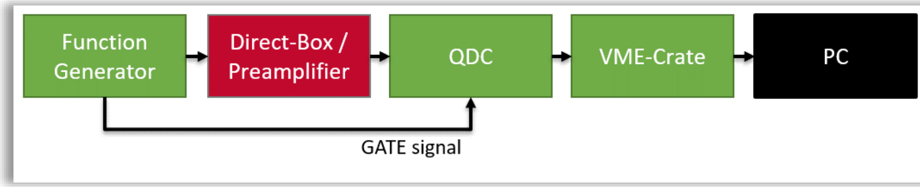
```
Double_t tquenchPfour ( Double_t *x, Double_t *par )
{
        Float_t xx = x[0];
        Double_t f = par[0] * (1 - std::exp( - xx*par[1]/par[0] ) );
        Double_t ff = f  + par[3] * ( xx*par[1] - f ) ;
        f = ff * ( par[2] + 1)/(par[2] + (xx*par[1]/f)) ;
        f = f * ( 1 + par[4]*std::exp( - xx*par[1]/par[0]  )) * ( 1 + par[5] );
        return f;
}
//{#pixels, scalefactor=1, timeConstant1, timeConstant2, Crosstalk, Afterpulse}
```

First order exp. behavior as before

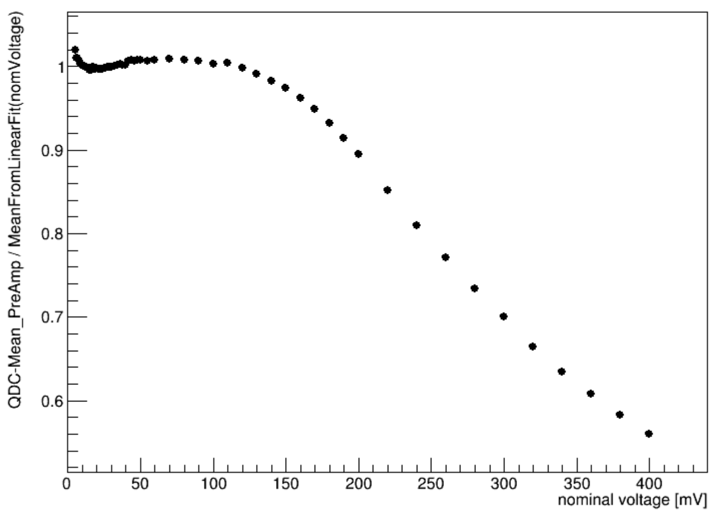
by: K. Kotera

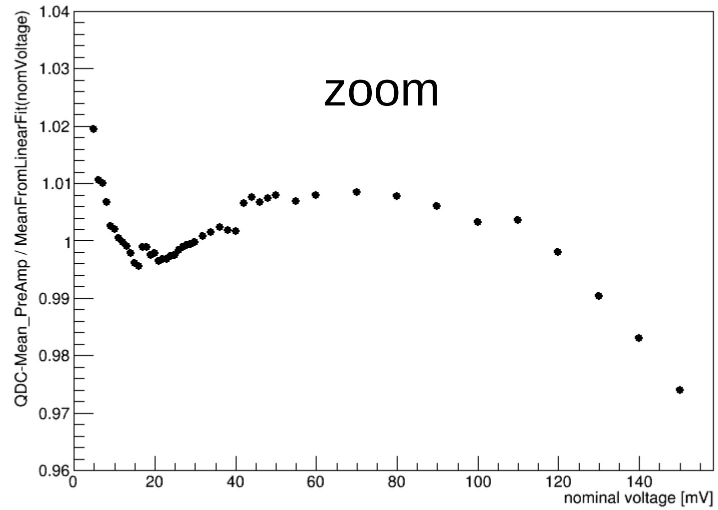
PreAmp Characterization



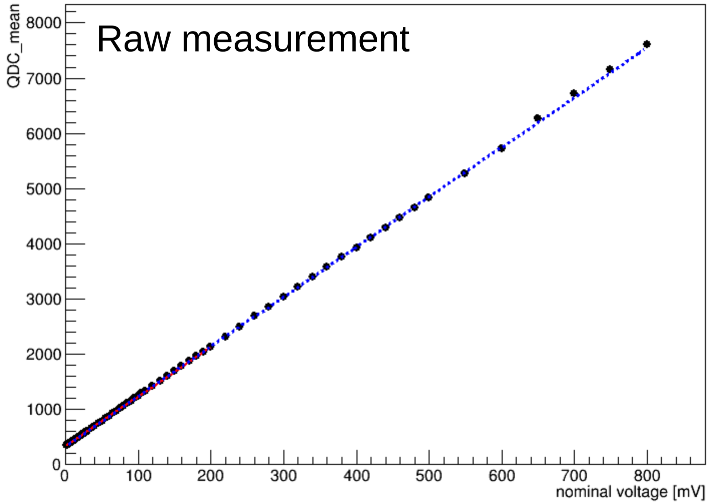


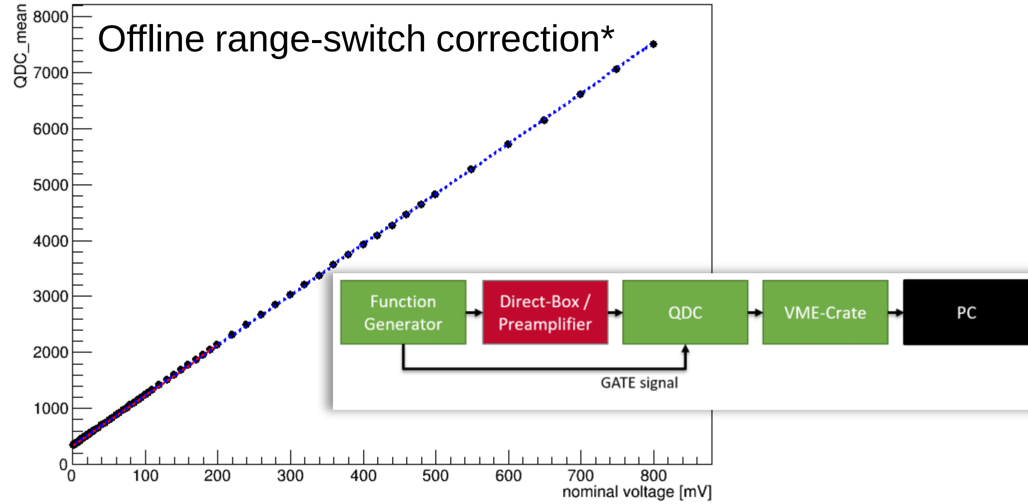
A clear saturation of the preamplifier is visible, starting around > 130 mV input voltage, which corresponds to a resulting output voltage of around 1V , assuming the amplification is 8. For lower values, the linearity is given by approx. 1 to 2 %.

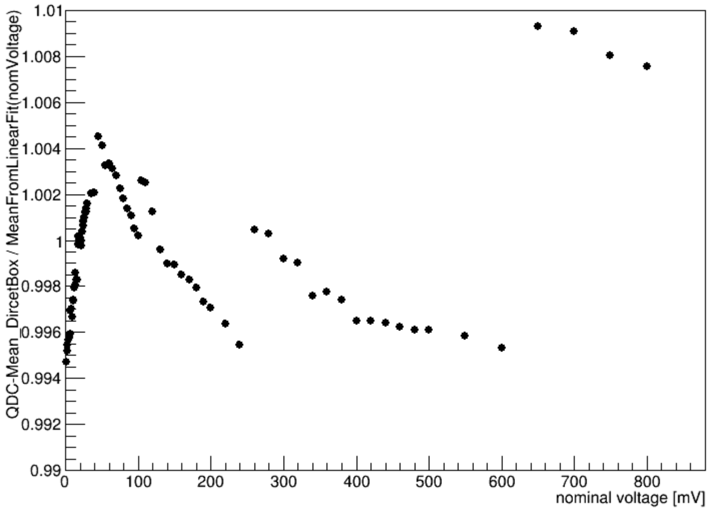


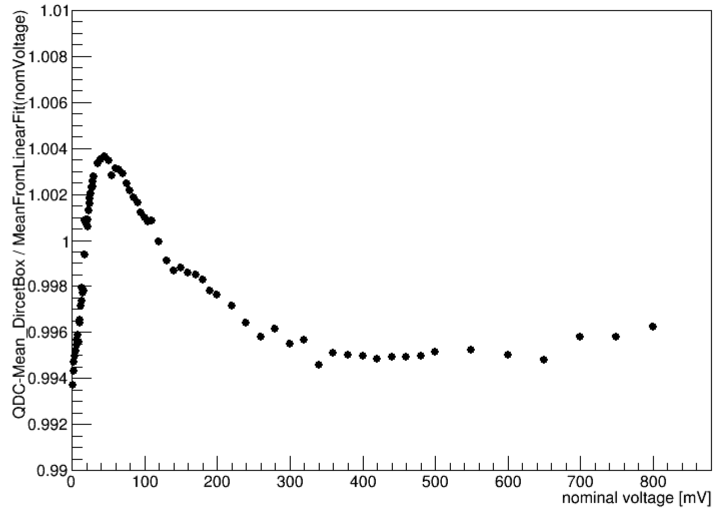


Direct Box Characterization (linear within 1% dev.)









*

at the position of change:

g_QDC_mean_correction[fileNumber] = ((g_QDC_mean[fileNumber-1]-g_QDC_mean[fileNumber-2]) + g_QDC_mean[fileNumber-1])-g_QDC_mean[fileNumber];

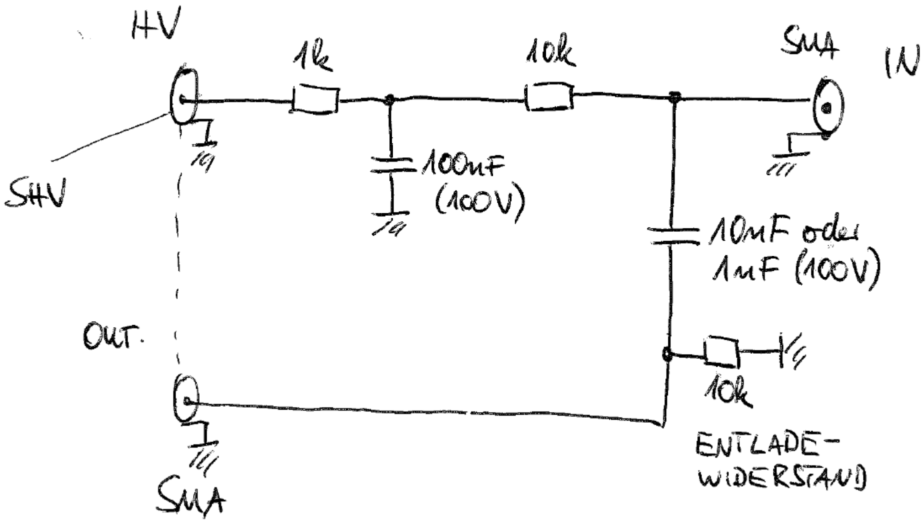
at the following positions without further change:

g_QDC_mean_correction[fileNumber] = g_QDC_mean_correction[fileNumber-1];

Correction:

g_QDC_mean[fileNumber] = g_QDC_mean[fileNumber] + g_QDC_mean_correction[fileNumber];

Direct Box Circuit



Digitization

```
/*---------------------- simulate SiPM behaviour ---------------------------*/
    //          energy mips to pixels
    //          saturate
    //          smear
    //          unsaturate
    //          energy pixels to mip

Ahc2SiPMStatisticProcessor:

float simHitPx = simHitMIP * lightYield;                                            // energy MIP -> pixels
float satHitPx =  satFunc->saturate( simHitPx );                                    // saturate
float prob = satHitPx / satFunc->getNeffPix();                                      // calculate p for binomial smearing
float satSmearedHitPx = _randomGenerator->Binomial(satFunc->getNeffPix(), prob);    // binomial smearing
if(_physicsMode)
        simHitADC = satSmearedHitPx * gainValue / interCalibrationValuePhys;        //energy pixels -> ADC
else
        simHitADC = satSmearedHitPx * gainValue;
```

In reconstruction, ADC is converted to Pixels, de-saturated and converted to MIP.

Statistical Method

3.2 Borel model of correlated noise

As shown in [7, 6], a possible model to describe the generation of correlated noise is by a Borel distribution

$$\Pi_k(\xi) = B_{k+1}(\xi) = \frac{((k+1)\xi)^k e^{-(k+1)\xi}}{(k+1)!}. \quad (11)$$

Such a model depends on a single parameter - ξ - taking values in the interval $[0, 1]$ and representing the average number of correlated counts that are generated at each step of the chain. The expected value

$$\mu = \frac{1}{1-\xi} \quad (12)$$

then gives the average number of correlated noise counts that are generated over the full chain.

3.3 Equations for the Borel model

Since the number of parameters has been reduced to two (λ and ξ), one may try and consider just two equations to be solved simultaneously. By choosing the two equations obtained from 9 for $k = 0$ and $k = 1$, the system may be reduced to

$$\begin{cases} \lambda = n_{21} - \xi e^{-\xi} \\ \xi\left(e^{-\xi} - 1\right) = n_{21} + \log n_1 \end{cases}, \quad (13)$$

where

$$n_{21} = \frac{N_2}{N_1}, \quad (14)$$

is the ratio between the areas of first two peaks in the charge spectrum.

With:

N_0 = total number of events

N_1 = all events with exactly one pixel fired (no XT)

N_2 = events with exactly 1 XT (2 pixels fired in total)

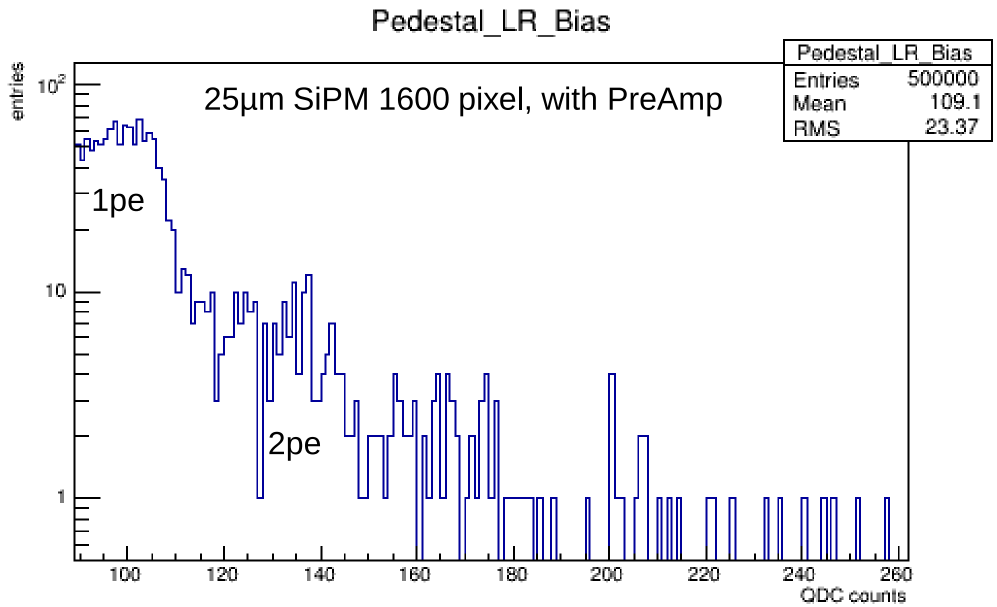
$n_1 = \frac{N_1}{N_0}$

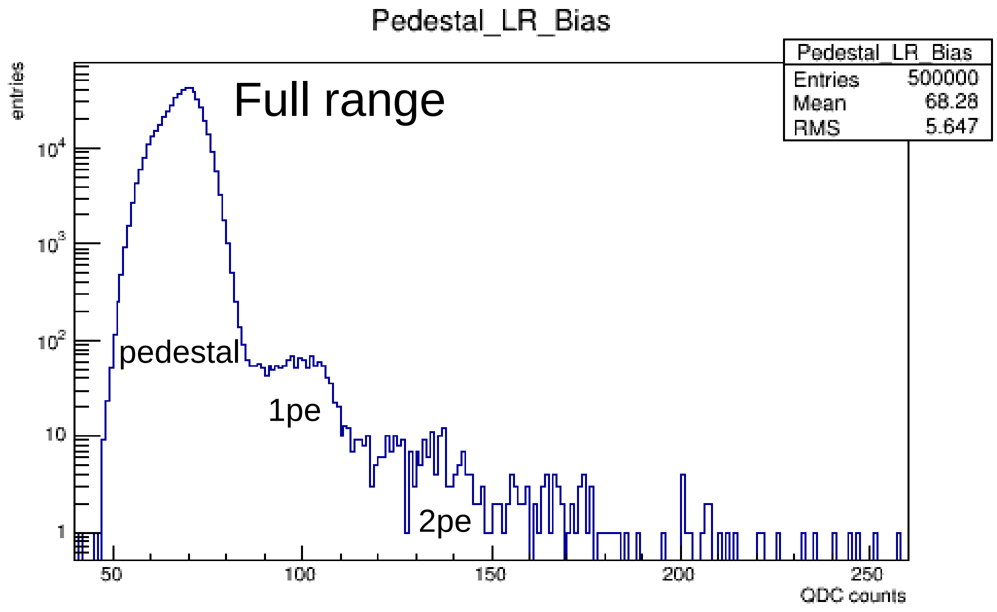
$$\xi\left(e^{-\xi} - 1\right) = \frac{N_2}{N_1} + \log\left(\frac{N_1}{N_0}\right)$$

$$\mu = \frac{1}{1-\xi}$$

Reference: https://arxiv.org/pdf/1710.11410.pdf

Analyzing randomly triggered QDC spectra without applying a light source





Pedestal without Bias: ~68
Gain: 33.61 +- 0.18
Mean selected spectrum: 109.1

-> $\frac{mean-pedestal}{gain} = 1.223$

But:
Statistics are very low!
And: hard to distinguish between pedestal and real 1pe events

Influence of left integration start:
-1bin: 108.3 -> 1.199
+1bin: 110.2 -> 1.256

Only a rough estimation possible.
Better: use method 1.

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PRISMA DETECTOR LAB

CALICE

AIDA 2020

Bundesministerium für Bildung und Forschung