Analysis of HGCAL Tileboard Data

Performance of HGCAL active elements

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AHCAL Main Meeting

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Overview

Performance of HGCAL active elements

- Motivation
- SiPM Gain measurements
- Light Yields with SiPM-on-Tile
- Read-out system upgrade
- Challenges with irradiated devices

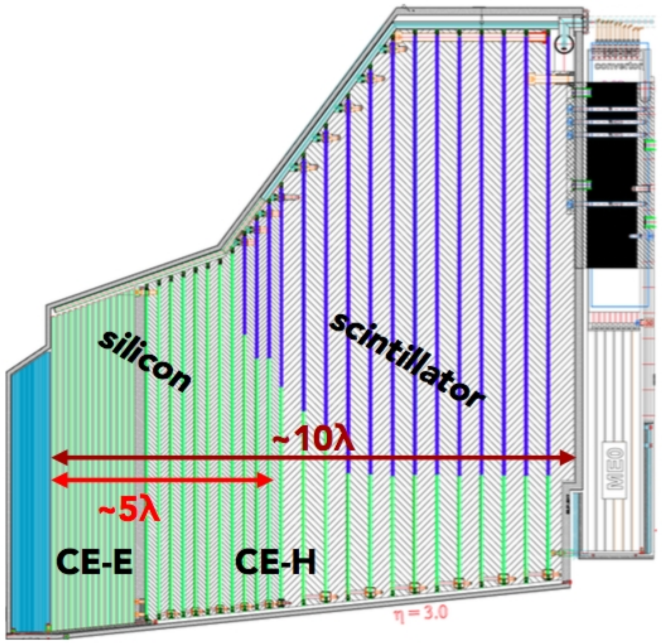
High Granularity for the High Luminosity LHC

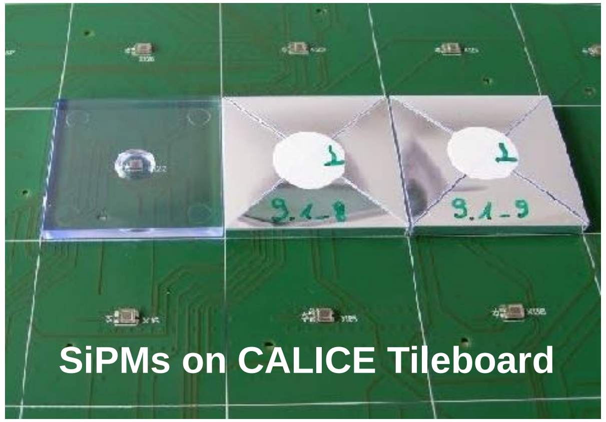
Phase II Upgrade of the CMS End-Cap Calorimeter (HGCAL)

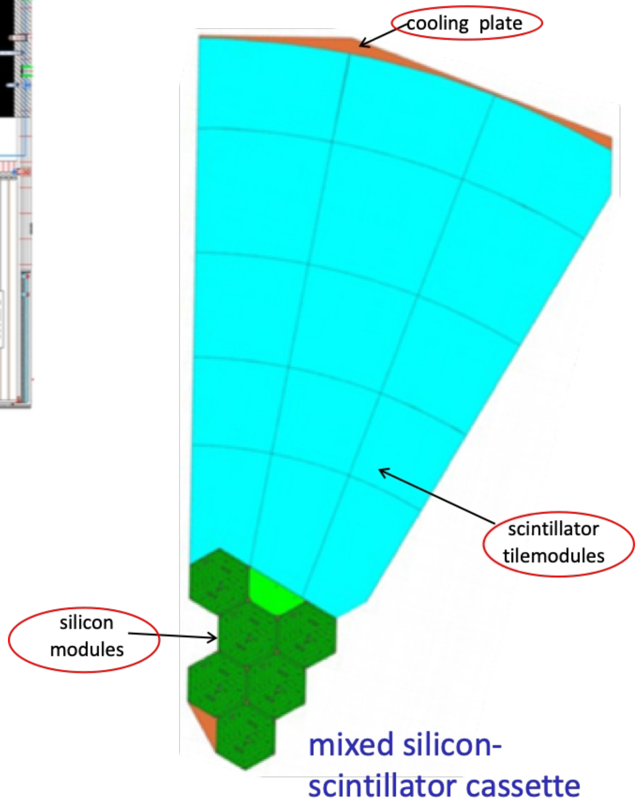
- The phase 2 upgrade of the CMS detector will replace the current endcap calorimeter with a high granularity calorimeter (HGCAL)

- The active area of CMS endcap calorimeter (HGCAL) will consist of:
  - silicon detector component : Silicon sensors
  - **scintillator component : SiPM-on-tiles**

- The Silicon and SiPM-on-Tile technology, originally developed for e+e- colliders by the CALICE collaboration





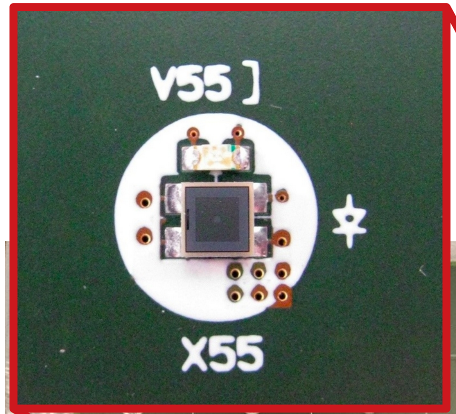


Scintillator Component of the Hadronic Endcap Calorimeter

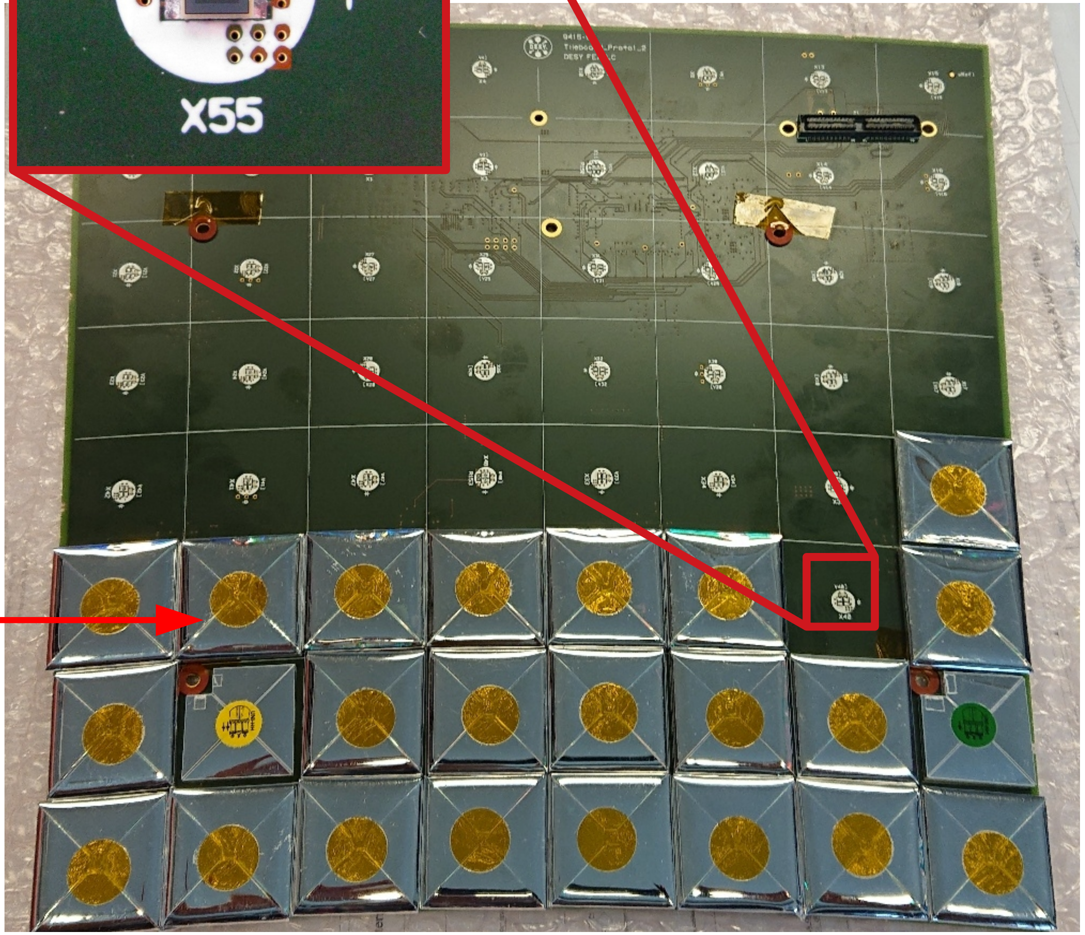
Tileboard and Front End Electronics

- The signals from SiPM-on-tiles are read out by the HGCROC front end electronic ASIC
  - Final version under development

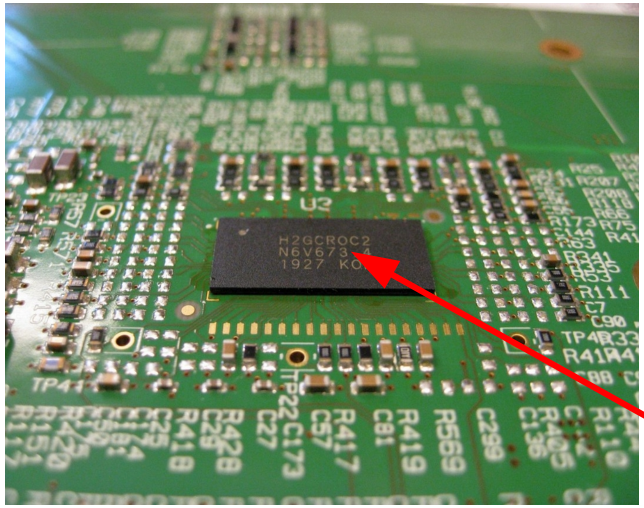
- Tileboards hold the SiPMs, scintillators, on-board electronics and LED system.
  - Increases in size when going away from the beamline



Silicon Photomultiplier with white reflection area for better light coverage



Scintillator tiles on the front side of the tileboard

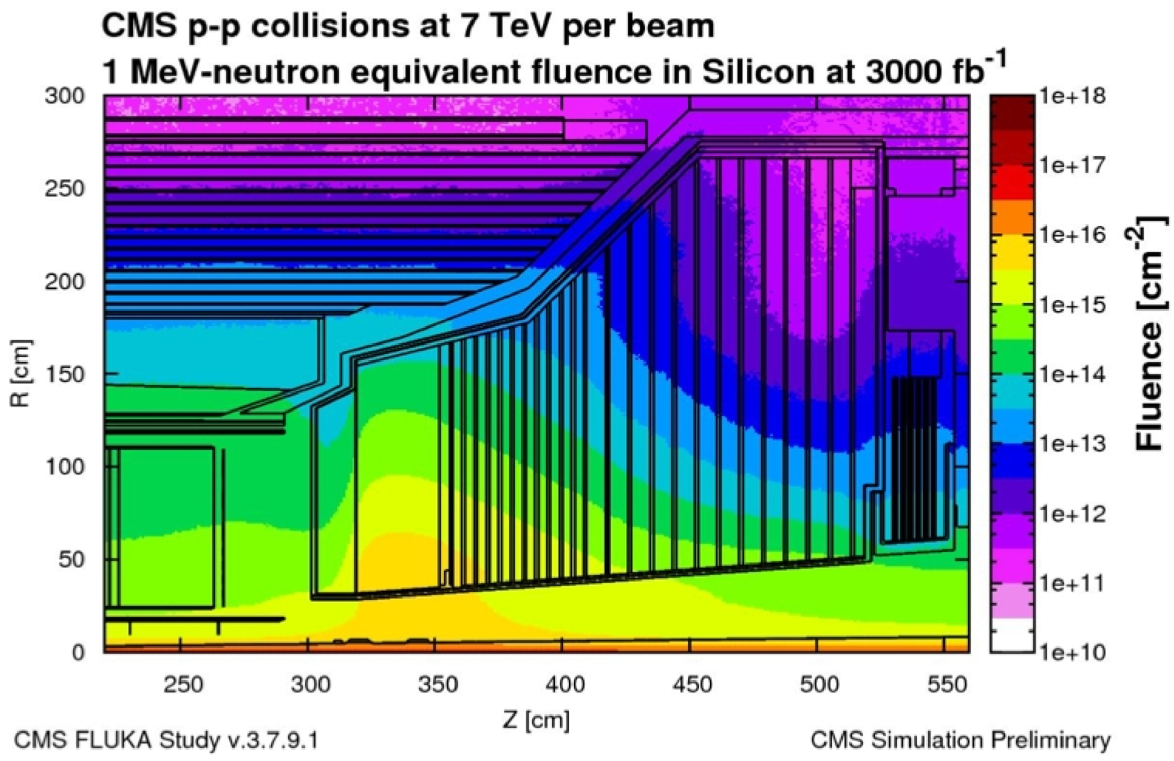


HGCROC on the back side of the tileboard

Scintillator Component of the Hadronic Endcap Calorimeter

Motivation

- Need to calibrate each cell of the detector up to end of life
  - Scintillator will degrade by about a factor of 2
  - SiPM noise will increase from negligible to 20-30% of MIP signal, beyond which calibration becomes doubtful
- Need to know starting point (beginning of life) performance well, under realistic conditions (with HGCROC)
- Need to validate dependence on tile and SiPM size, and on scintillator material, in final configuration with SiPM and reflector
- Need to understand impact of increased radiation-induced SiPM noise, and validate temperature dependence



Tileboards at the Test Beams

Introduction

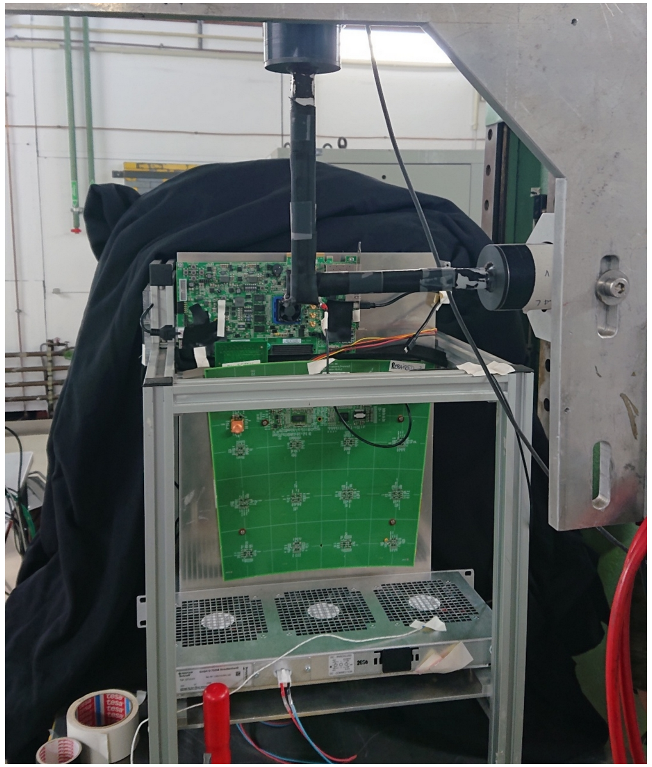
- 6 test beams took place between October 2020 and October 2021 (5 at DESY, 1 at CERN SPS)

- Two systems were used :
  - **Two tileboards (TB1.2 and TB1.3) with the KCU DAQ :** used in all 6 test beams
  - **TB2 tileboard with the TB-tester DAQ :** used in the October 2021 test beam

- All tileboards consisted of **Hamamatsu HDR-2 SiPMs of 2 mm² and 4 mm² active area with a 15µm pitch** and custom radiation hard packaging.

- Many different scintillator tiles were used at these test beams.

TB1.2

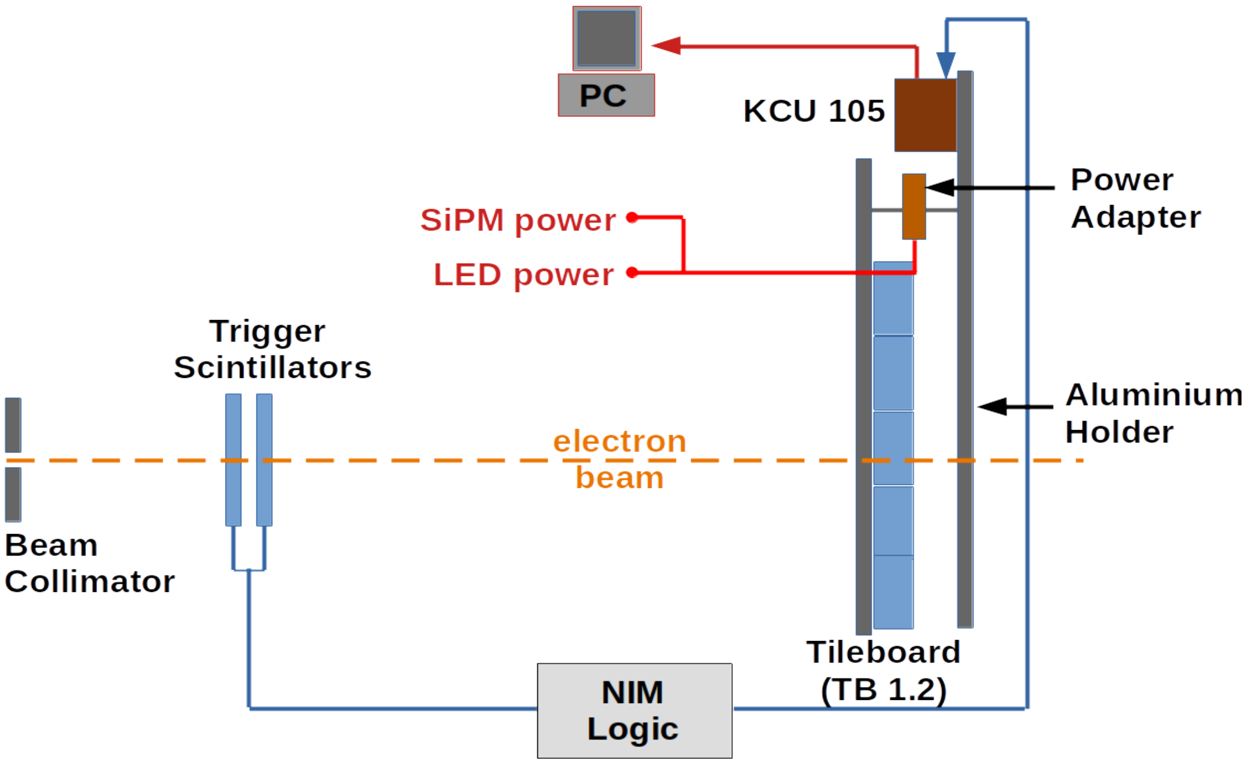


TB1.3

Tileboards + KCU DAQ at the DESY Test Beams 2020 and 2021

Beam Test Setup

- KCU105 module is used for data acquisition
  - Commercially available FPGA evaluation board



- Measurements:
  For different over-voltages and conveyor gains
  - **SPS data using LED system** (35,000 events per channel) → SiPM gain measurement
  - **Beam data with 3 GeV electrons** hitting each channel (10,000 events per channel) → Most probable value measurement

- The light yield is then calculated as:

$$Light\ Yield = \frac{MIP\ MPV}{SiPM\ gain}$$

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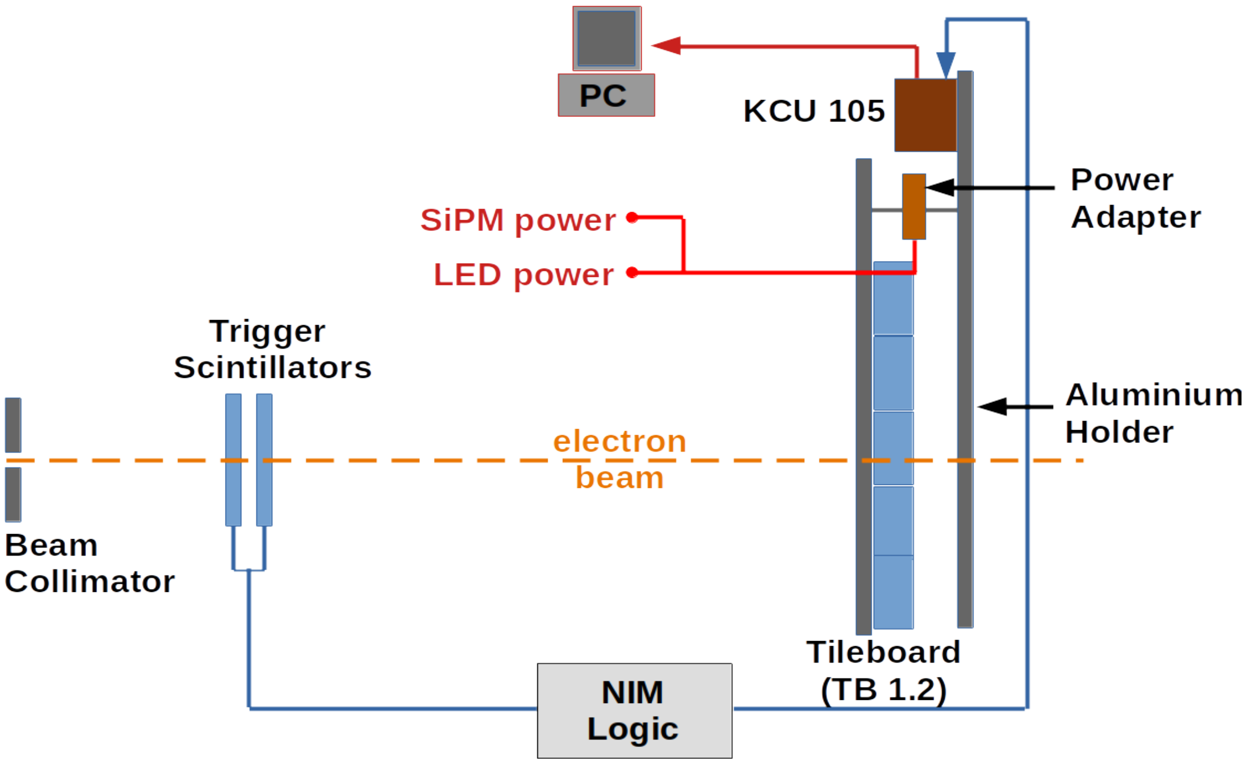

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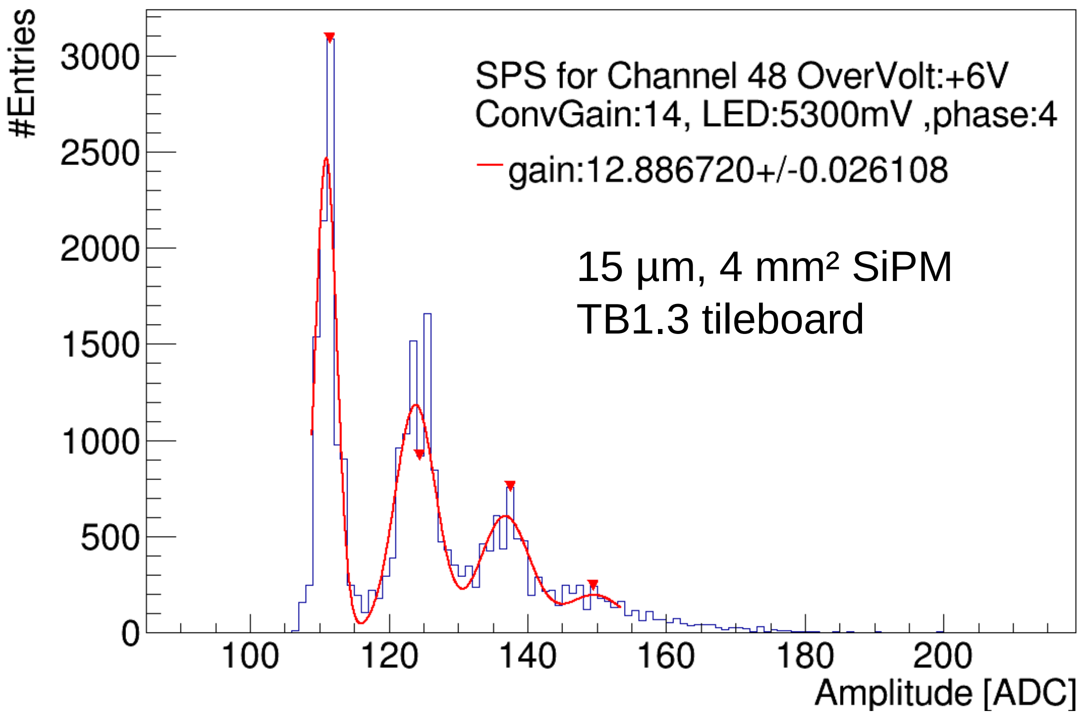
- Overview:
  - DNL correction to obtain the SiPM gain
  - SiPM gain estimation at overvoltage = 2V
  - Template-fit based MIP MPV extraction
  - Bias voltage based light yield correction

SiPM
Gain Measurement

Measurement of Gain using Single Photon Spectra

Using on-board LED system

- SiPMs on the board were illuminated using the on-board low-intensity LED system to obtain single photon spectra.
- **SiPM Gain** : mean difference between peaks
- For test beams during 2020 and early 2021:
  - Pulse from SiPM was sampled at phases 4 and 9
  - Amplitude was taken using correction factor obtained by evaluating the LED pulses in the lab (see backup for more information)
- For test beams from April 2021 onwards:
  - Pulses sampled at phases 1 to 7 and the maximum value is taken as pulse amplitude

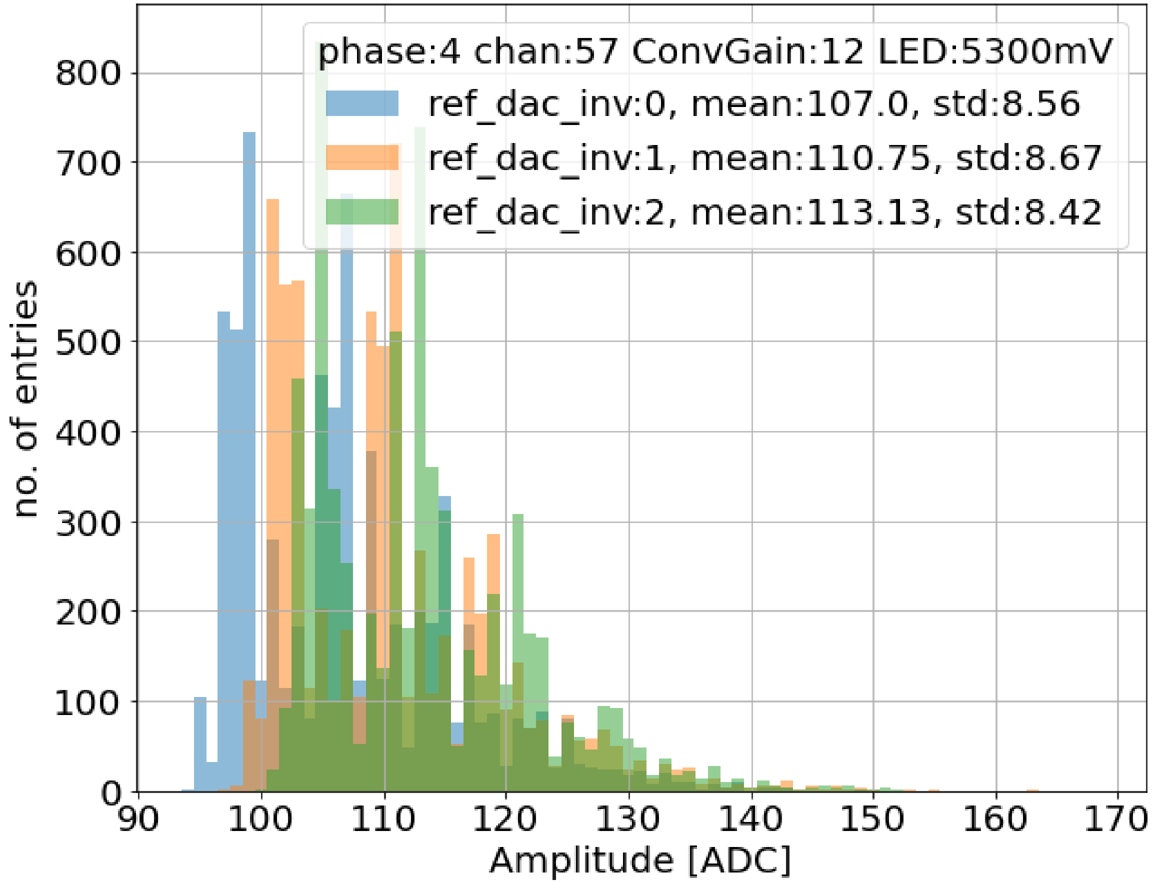


- Bin-to-bin fluctuations are caused by a **differential non-linearity** present in the HGCROC.

Averaging the DNL Effects by Pedestal Shifting

For ConvGain 12, OverVolt: 4V ; for LED Bv > 5.2 V

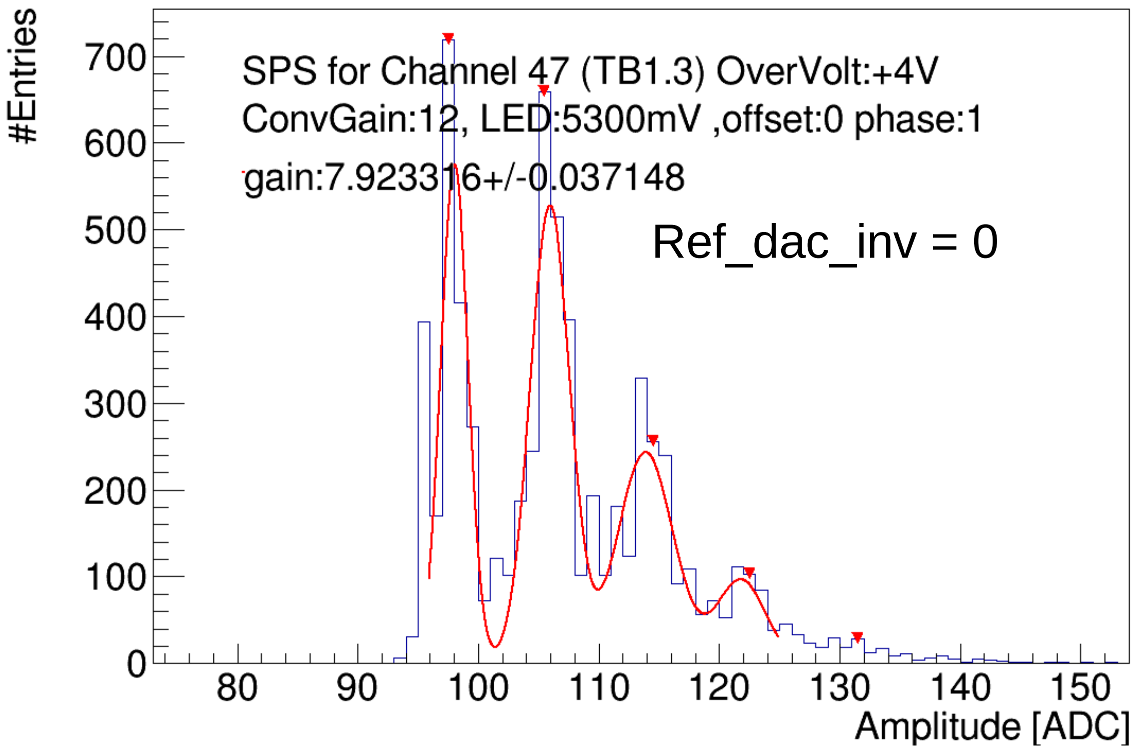
- HGCROC parameter Ref_dac_inv is capable of shifting the pedestal by ~ 3 ADC per unit change (to nearest whole number)
  - If DNL is ADC dependent, by taking data at multiple pedestal values, one can average the DNL effect
- Three datasets were taken with Ref_dac_inv parameter of all active channels at default value and by incrementing by 1 and 2.

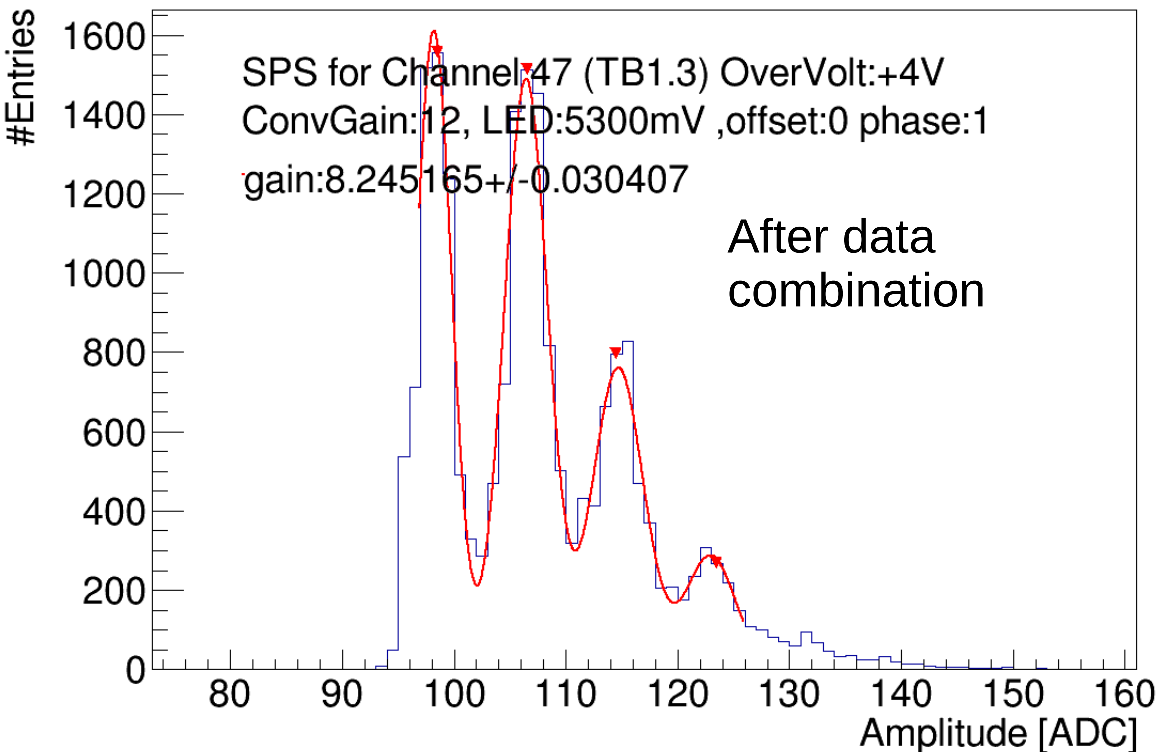


Comparison of SPS before and after averaging

For ConvGain 12, OverVolt: 4V ; for LED Bv > 5.2 V

- Three datasets were combined as follows
  - If Ref_dac_inv = 1 : then 3 ADC was subtracted from all data
  - If Ref_dac_inv = 2 : then 6 ADC was subtracted from all data

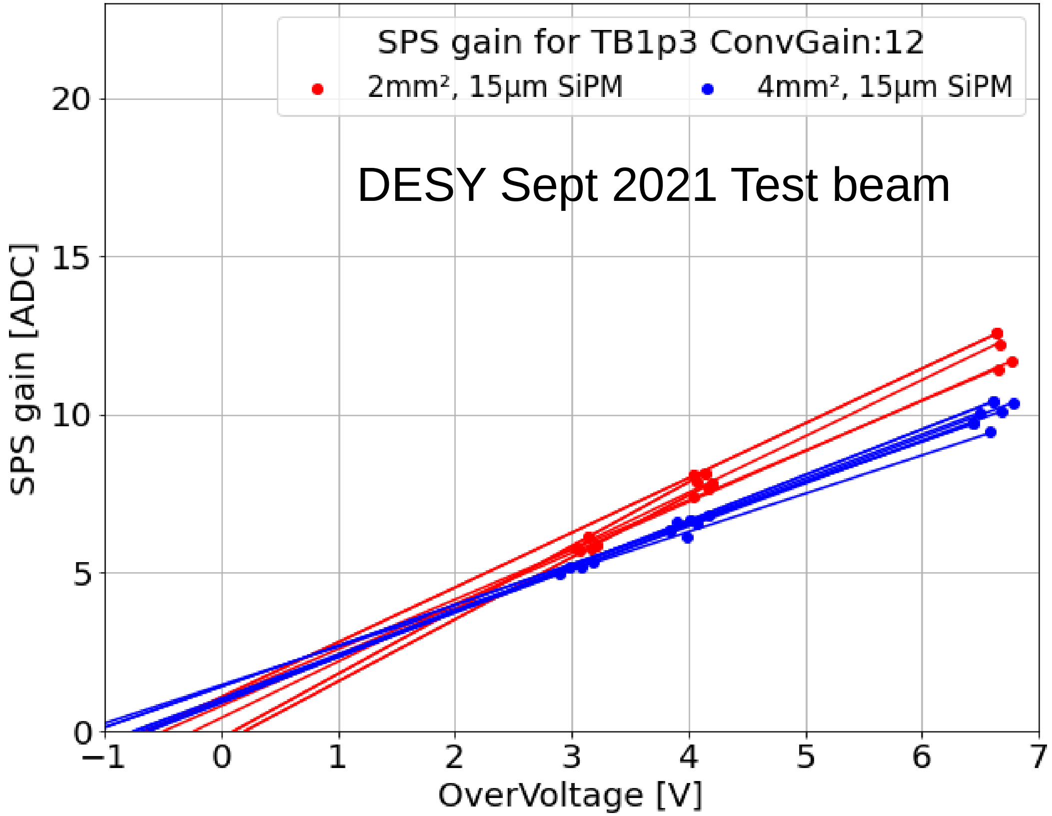


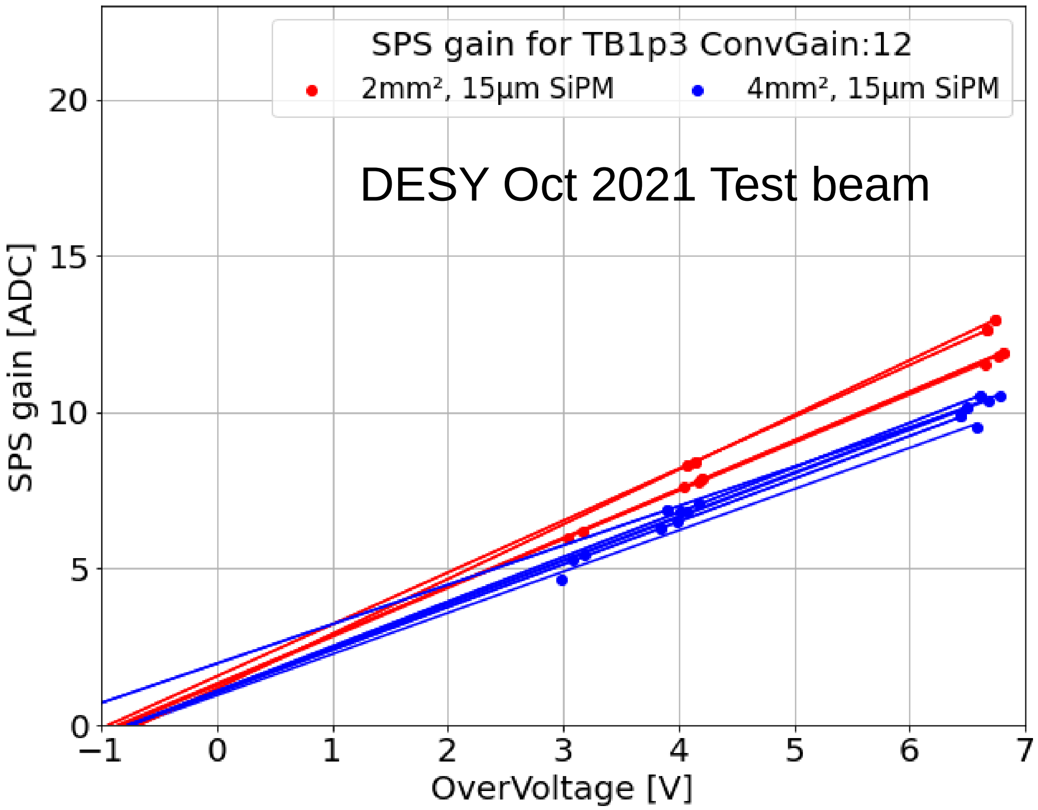


Estimation of SiPM gains for Over Voltage = 2V

Global gain estimations for all channels of TB1.22 and TB1.3

- Despite having SPS data taken for lower overvoltages, the limited resolution prevents a measurement of SiPM gain at lower overvoltages.
- Therefore a **first order polynomial** was used to estimate the **SiPM gains at the missing over voltages especially OV=2V**

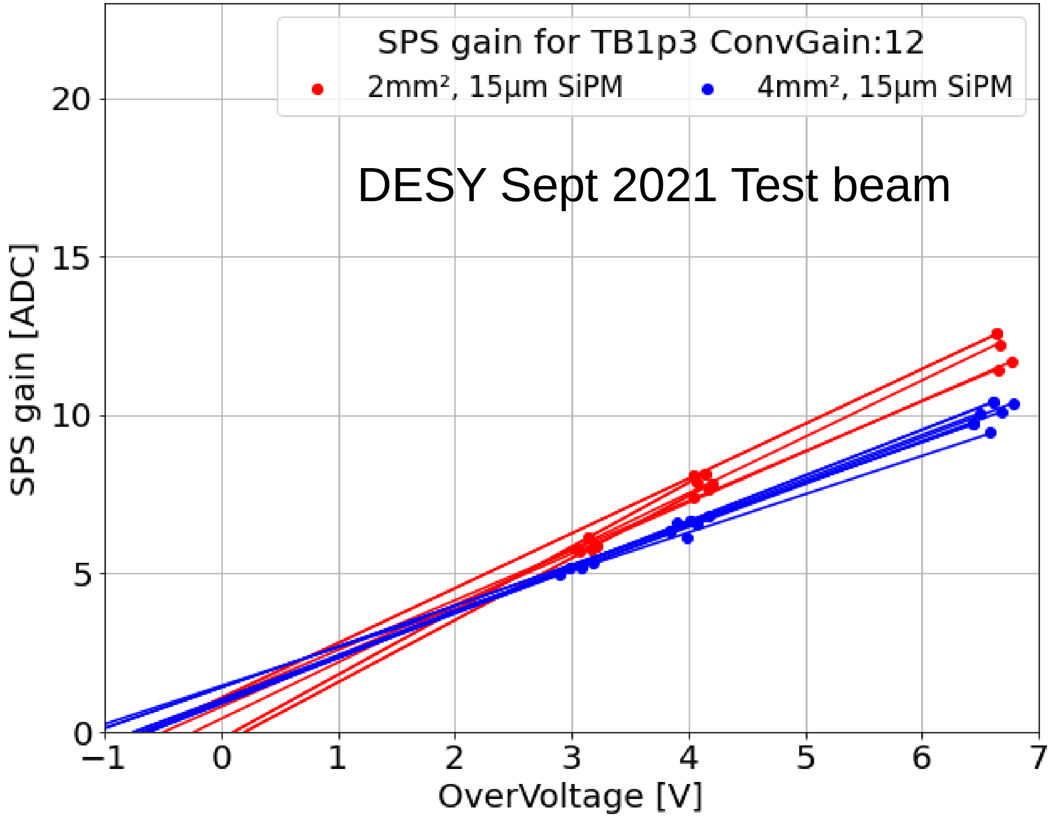




Summary so far

SiPM Gain measurement

- DNL limits the gain studies: measurements at low OV not possible
- Large extrapolation uncertainties affect the breakdown voltage determination
  - Spread is much larger than what is predicted from data sheets (+- 300 mV) and confirmed on test benches.
- Observed spread in extrapolated breakdown voltages not yet quantitatively explained
- Performance estimates at OV = 2V also only from extrapolation

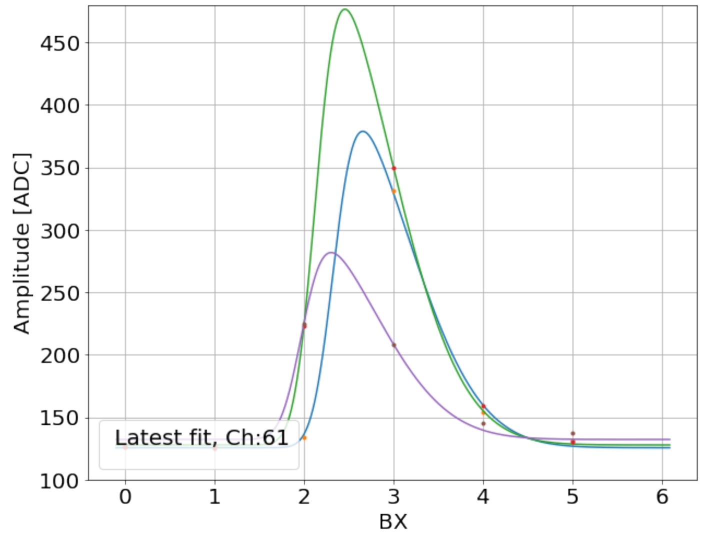


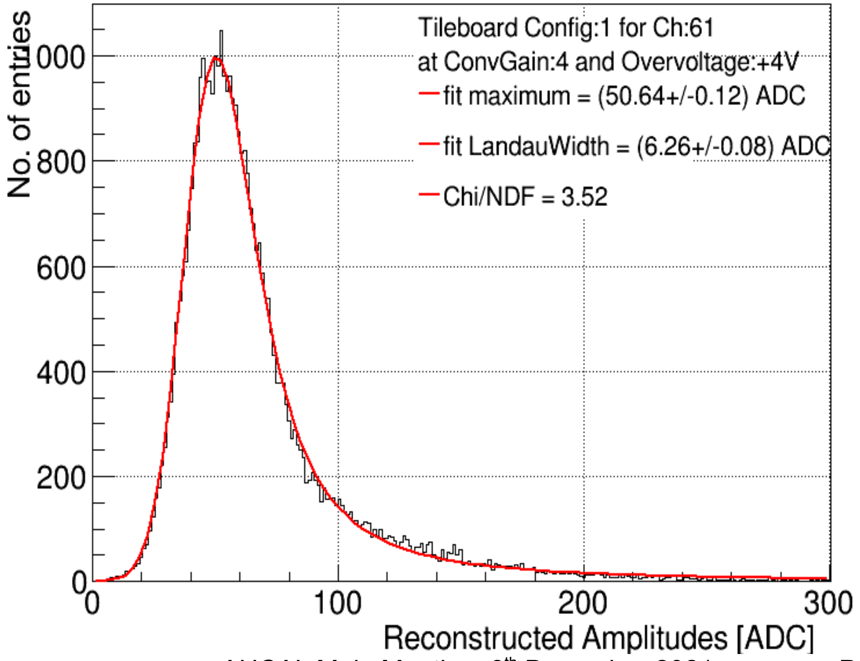
SiPM-on-Tile
Light Yield

Measurement of the Most Probable Value

Pulse Amplitude Extraction using a Template Fit

- HGCROC samples the signal at 40 MHz corresponding to the collision frequency
- DESY beam is non-synchronous to the system. Therefore pulse maxima needs to be extracted offline
- Pulse amplitude is reconstructed from the maxima of a **multi-sample event-by-event template fit**
  - 6 points sampled at 25 ns rate per event are fitted using a **skewed-Gaussian fit with fixed std. dev. and skewness.**
  - Fixed parameters based on pulses from sampling scan using the LED system
- The **most probable value (MPV)** is extracted from the resulting spectra obtained from a minimum ionizing particle (MIP) in order to calculate the light yield.

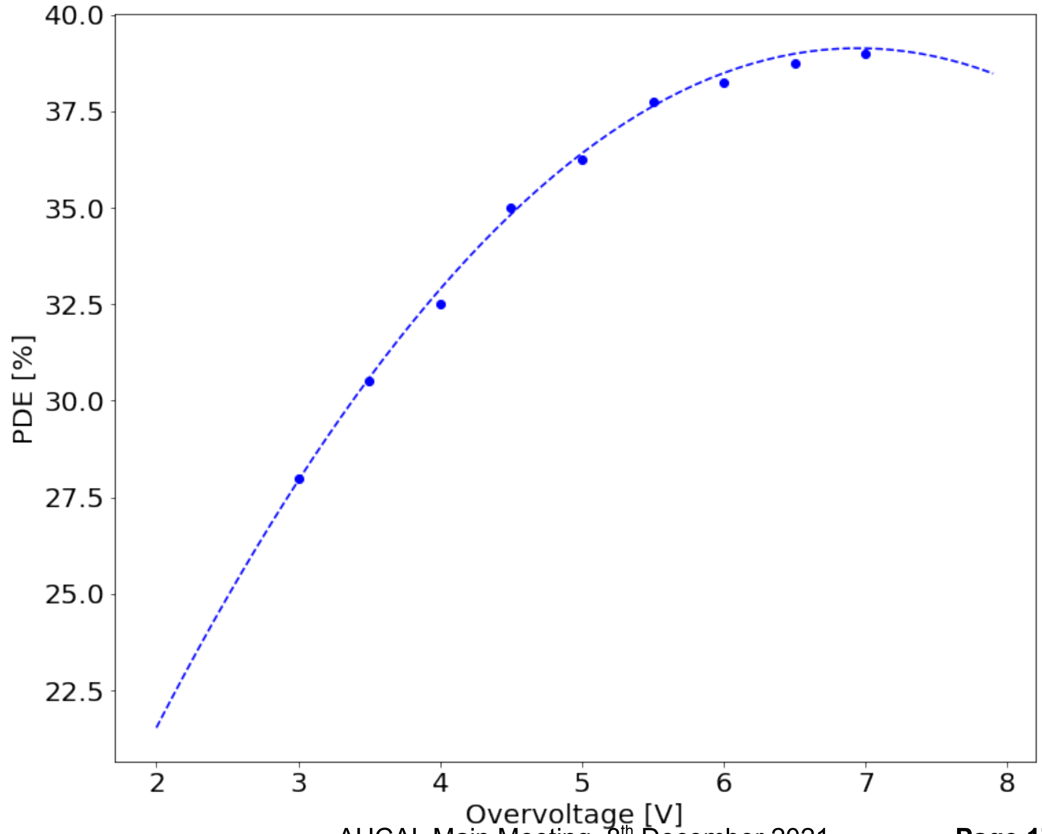




Bias Voltage Correction of Light Yields Measured

Correction using Quadratic Function on the Photon Detection Efficiency (PDE)

- Each SiPM on a given tileboard has a different breakdown voltage (< +/- 0.3 V). Therefore the light yields measured for each channel has a slight offset compared to each other.
- So, it is important to do a correction before comparing the the light yields calculated as described before.
- Light yield is proportional to PDE. Hence it is possible to use the PDE curve given in the data sheet to scale the light yields



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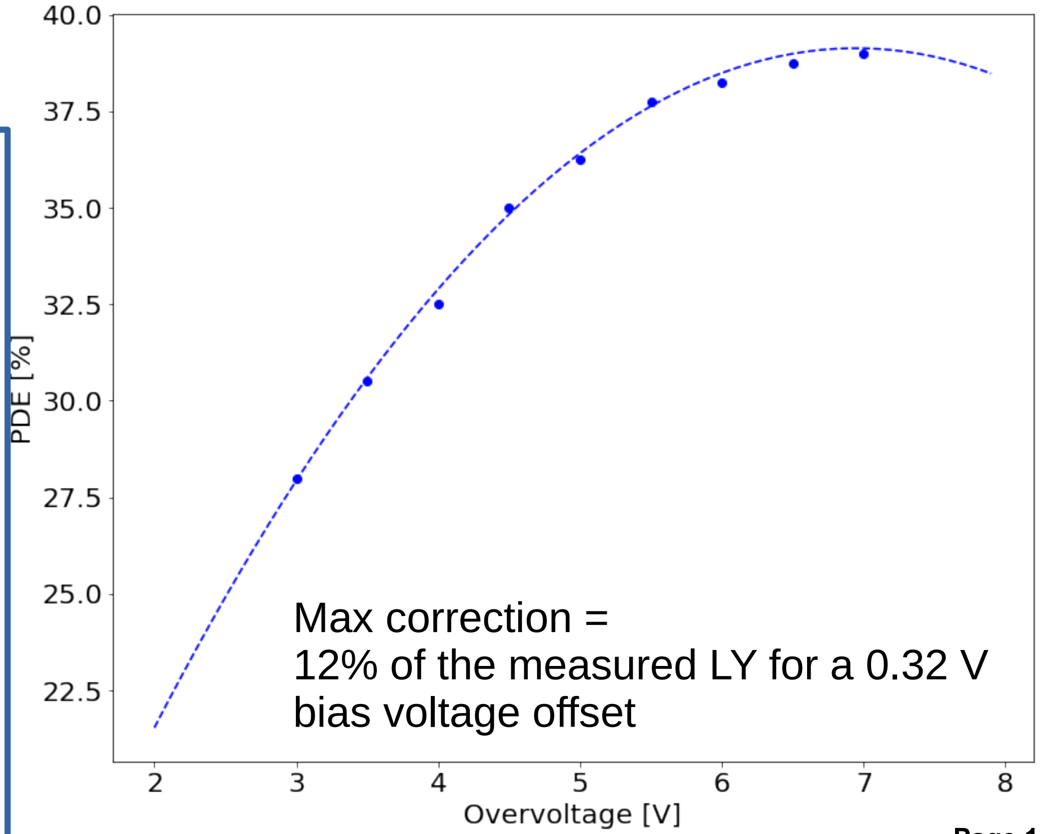
- Light yield is proportional to PDE. Hence it is possible to use the PDE curve given in the data sheet to scale the light yields
  - Step1: **PDE can be assumed to scale as a quadratic function**

    Fitting a quadratic function, the coefficients (p,q,r) of the function can be found.
  - Step2: Calculate the light yield using the MIP MPV and SiPM gain with the overvoltage offset
  - Step 3: **Using the function below, find the new light yields**

$$(y_2)=(y_1)*\left(\frac{p x_2^2+q x_2+r}{p x_1^2+q x_1+r}\right)$$

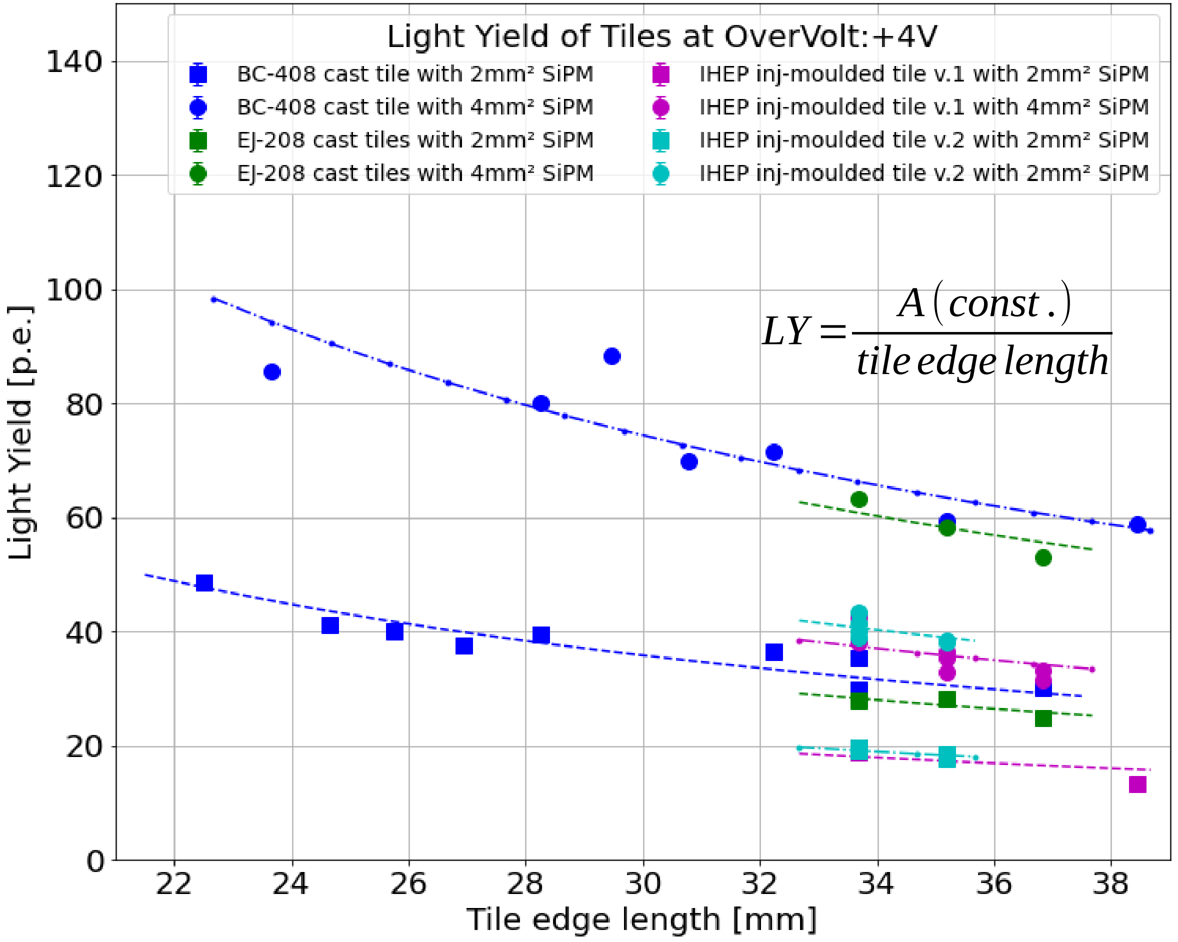
where:

y2 = bias voltage corrected light yield
y1 = measured light yield
x1 = overvoltage of measured LY
x2 = needed overvoltage



Light Yield Measurement at Over Voltage = 4V

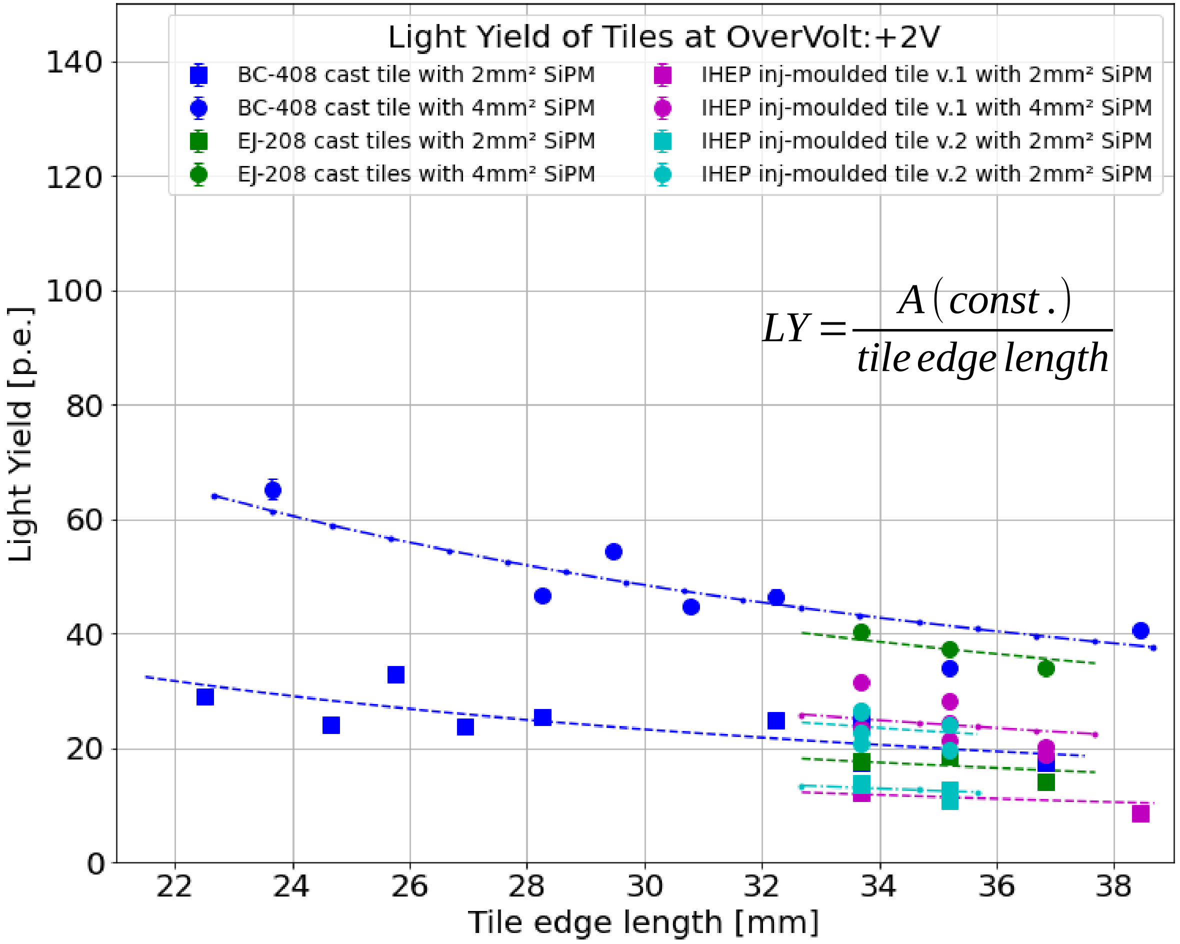
Comparison of light yields with different SiPM sizes and tiles



- Consistency checks: LY(4mm²)/LY(2mm²)
  - **Expected value = ~ 2.06**
  - IHEP injection-molded v.1 = 2.07
  - IHEP injection-molded v.2 = 2.13
  - BC-408 cast = 2.08
  - EJ-204 cast = 2.15
- Systematic uncertainties ~10%
- Expected dependencies on tile and SiPM size are fulfilled within errors
- Combination of all measurements provides a realistc estimate of uncertainties

Light Yield Measurement at Over Voltage = 2V

Comparison of light yields with different SiPM sizes and tiles



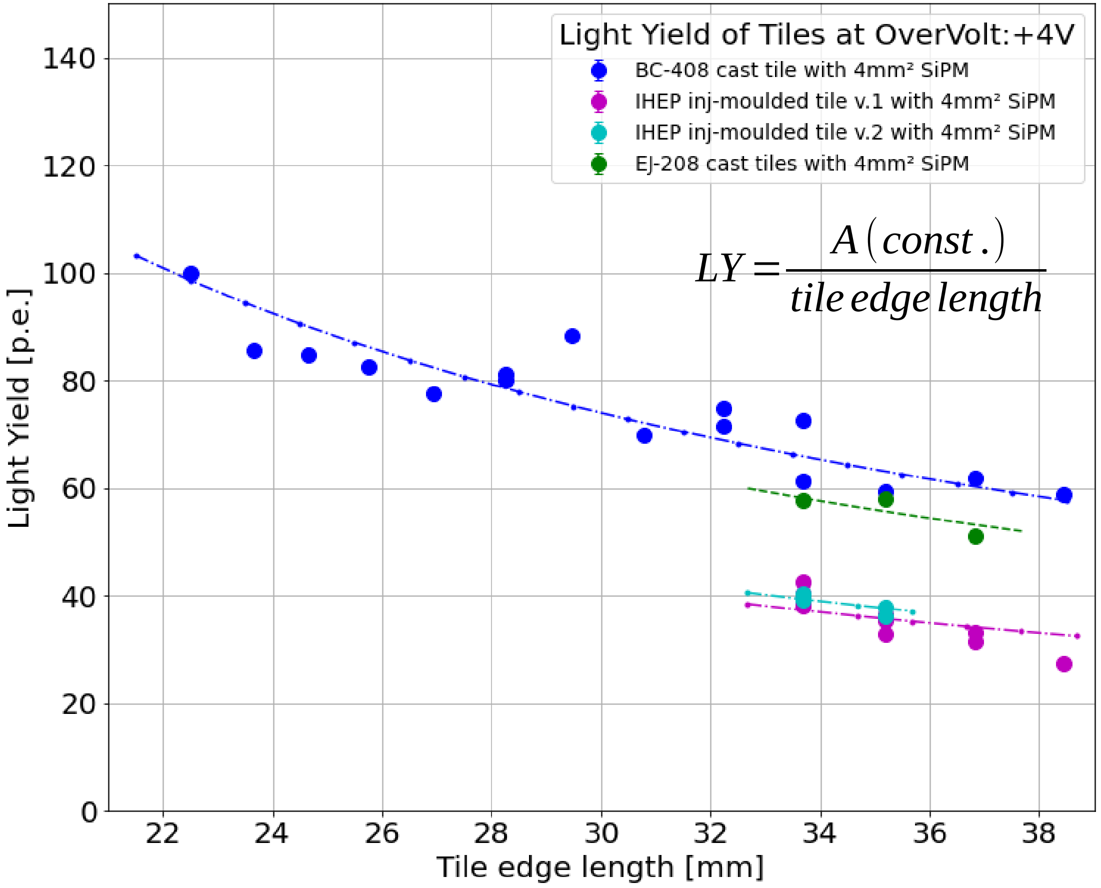
- Consistency checks: LY(4mm²)/LY(2mm²)
  - **Expected value = ~ 2.06**
  - IHEP injection-molded v.1 = 2.12
  - IHEP injection-molded v.2 = 1.83
  - BC-408 cast = 2.09
  - EJ-204 cast = 2.21
- Systematic uncertainties ~10%
- Expected dependencies on tile and SiPM size are fulfilled within errors
- Combination of all measurements provides a realistc estimate of uncertainties

Other consistency checks showed that all results are reproducible between the different tile boards, different test beams and different conveyor gains (see backup slides).

Model for Light Yield Measurements at fixed Over Voltage

Comparison of light yields with different SiPM sizes and tiles

- Since the results satisfy the basic consistency checks, it is possible to combine the two data sets for 4mm² and 2mm² SiPMs to estimate the final light yields by multiplying light yields of 2mm² SiPMs by 2.06 and using a common fit



$$LY = \frac{A(const.)}{tile\,edge\,length}$$

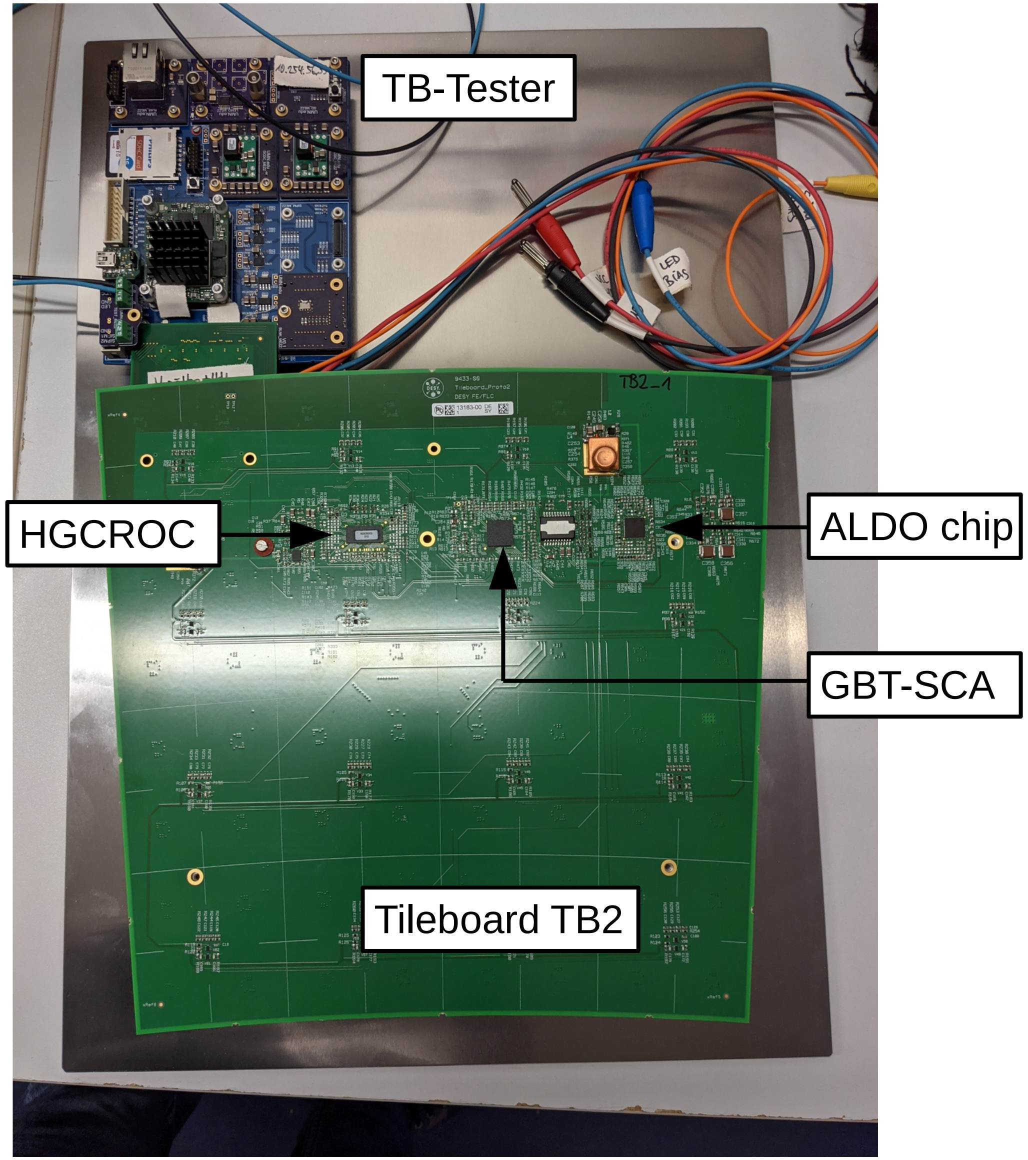
- Ratio comparison of different tiles for OV=4V
  - **IHEP injection-molded (v.2/v.1) = 1.05**
  - **(IHEP injection-molded v.2)/(BC-408 cast) = 0.59**
  - **(BC-408 cast)/(EJ-208 cast) = 1.13**
- Same method can be followed for OV=2V and results yield similar ratios (see backup)
- IHEP injection-molded versions: 17-20% claimed, probably optimistic
- Injection-molded vs cast: expect 50-70%, depending on materials and procedures

Read-out System Upgrade

Tileboard TB2 + TB-Tester DAQ at the DESY Test Beam

At the DESY test beam of October 2021

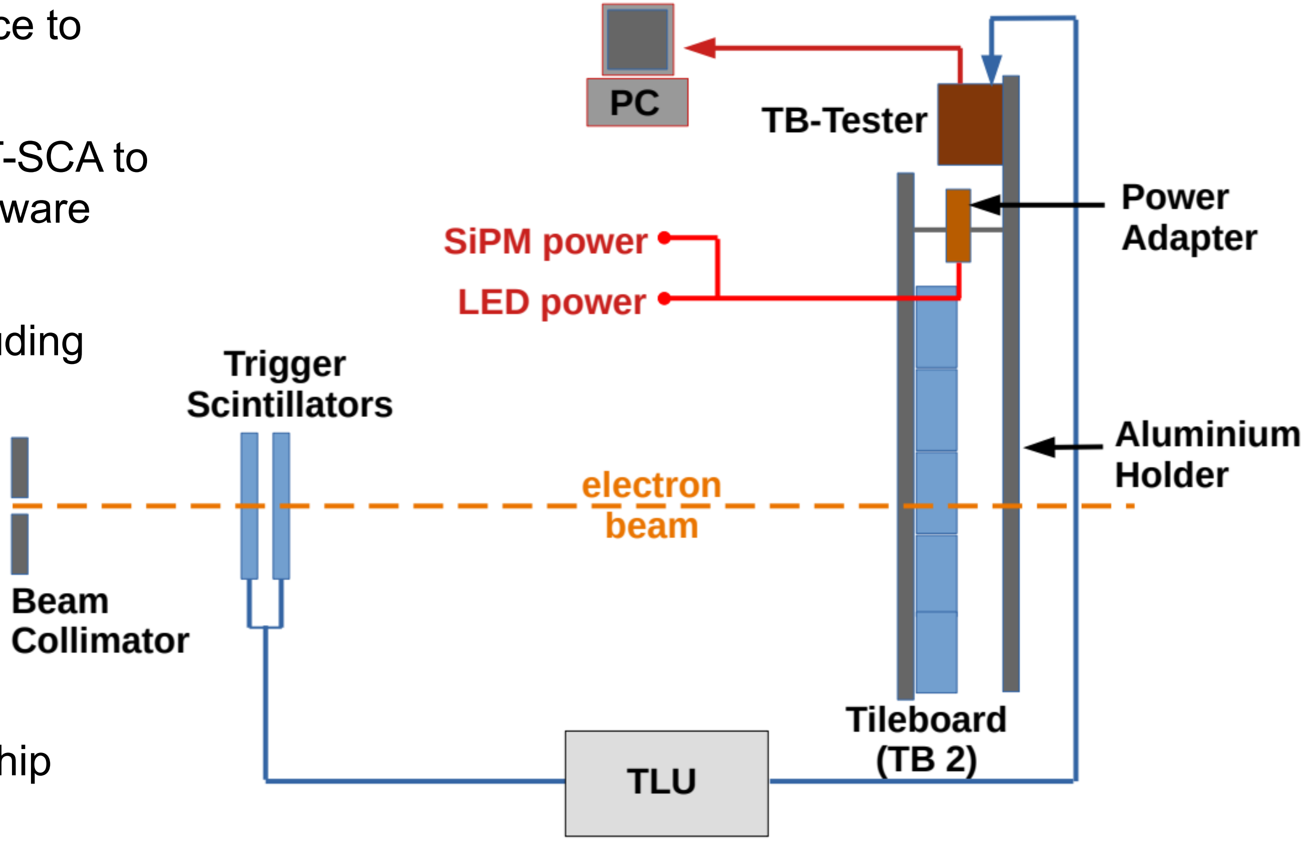
- All test beams until October 2021 used the KCU105 for data acquisition from the tileboards.
  - Lacks many functionalities including recording timestamps and setting the SiPM bias voltages without a hardware change
  - Lacks scaling possibility to multi-tileboard systems, as need for quality control
- **TB-Tester DAQ** is very similar to the final DAQ to be used at the experiment and contains the functions lacking in the KCU105
- **TB2 tileboard** is also closer to the final tileboard to be used in the experiment
- **Objective of October 2021 test beam:**
  - First attempt of acquiring beam data with TB-tester DAQ at the October 2021 DESY testbeam



Beam Test Setup and Measurements : TB2 + TB-Tester

Beam Test Setup and Measurements

- **Setup:**
  - Used a beam and a pair of scintillators in coincidence to trigger events
  - The TB-tester speaks to the ALDO chip via the GBT-SCA to set the bias voltage supplied to the SiPMs : no hardware changes
  - Finally can access full slow control output data including temperature and voltage measurements

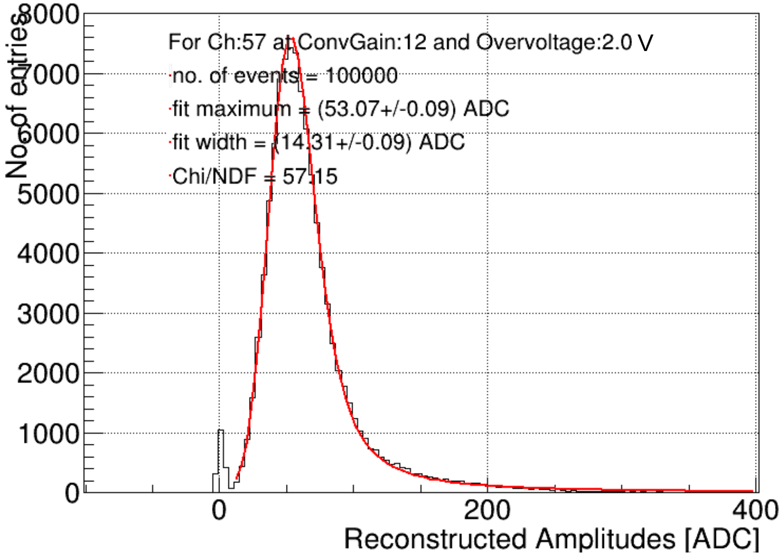


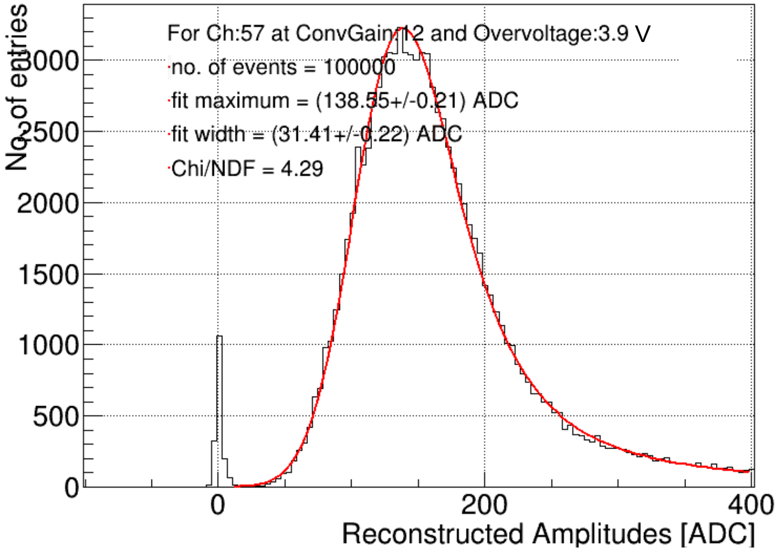
- **Measurements:**
  - Beam data with 3 GeV electrons
    - 100,000 events per channel (~ 7 kHz rate)
    - Overvoltages: 2.0V, 2.9V and 3.9V via ALDO chip
  - SPS data using LED system was not possible during the testbeam

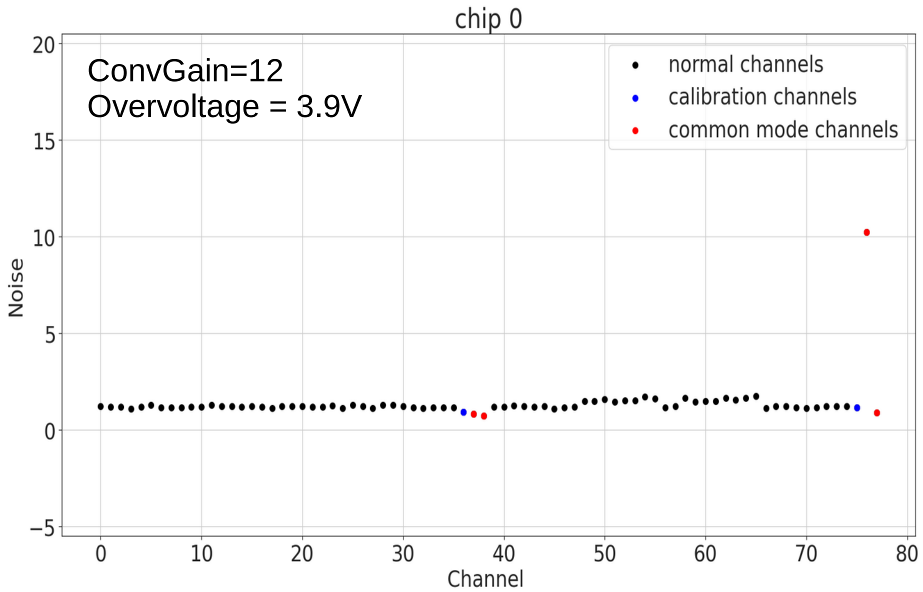
First MIP peak from TB2 and TB-Tester

DESY October test beam

- Output data format: ROOT trees
- Data analysis same as for the KCU setup
  - Template fit using 6 consecutive bunches of same event
- ALDO chip parameters changes the bias voltage
  - As evident from the increase of the MIP MPV with overvoltage, this works as intended
- No noise increase with respect to KCU DAQ (preliminary)







Summary of the Test Beam Results

Measurement of Light Yields from Test Beam Data

- **Test beam Analysis with TB1.3 + KCU:**
  - Data from six different test beams have been combined successfully taking all known effects due to different conditions and parameters to calculate the light yield.
  - Light Yields are consistent between different test beams and with expected dependences on SiPM and tile size from R0 to R24
  - A model based on $LY = \frac{A(const.)}{tile\ edge\ length}$ fit was used to estimate light yields from R0 up to R24 sized tiles
  - This model was used to compare tile materials including BC-408, EJ-208 and injection-molded tiles produced by IHEP Russia.

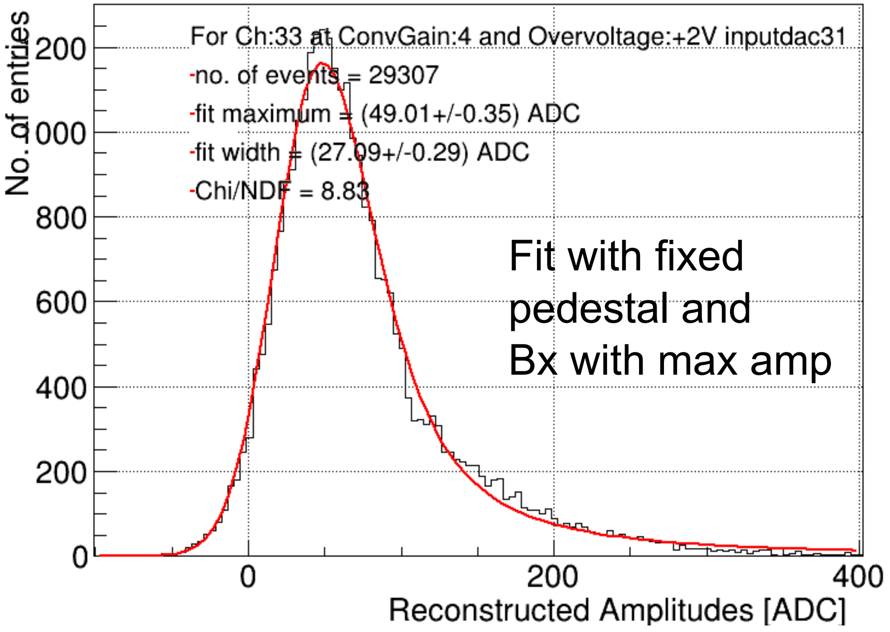
- **Test beam Analysis with TB2 + TB-tester:**
  - First MIP plots observed from TB-tester + TB2 combination
  - Single photon spectra not observed at the testbeam, but significant progress has been made in the lab after the testbeam to achieve this.

Tests with Irradiated SiPMs

MIPs with Irradiated SiPMs

TB 1.2

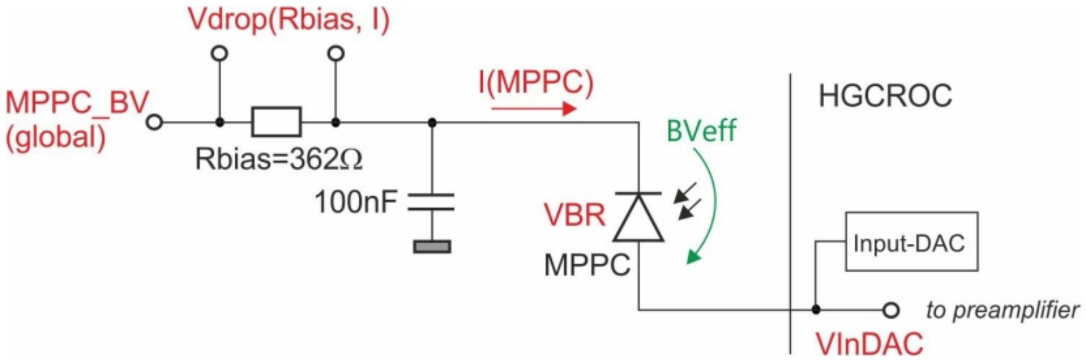
- Two irradiated SiPMs were mounted on the TB1.2 tileboard
  - Hamamatsu HDR-2 15µm SiPMs of 2 mm² and 4 mm² active area with custom radiation hard packaging
  - Irradiated to 2×10^{12} n/cm² at room temp. (JSI, Ljubljana) equivalent to ~5×10^{13} n/cm² at -30° C (expected end of life fluence)
  - Many open questions on the noise under the signal *work in progress*



Temperature Measurements with Climate Chamber

Measurement of RMS and MPPC current vs Temperature

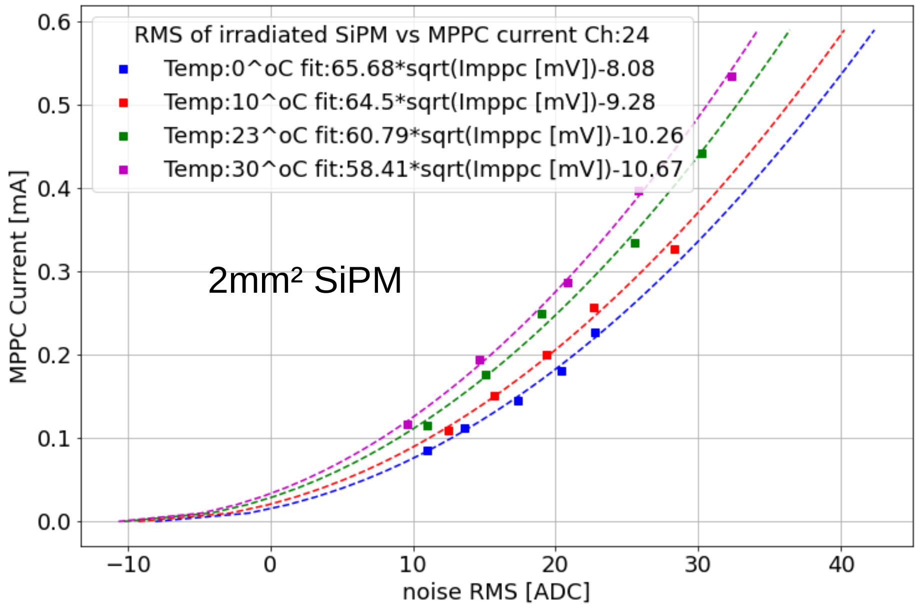
- S/N ratio used in the SiPM-on-tile model assumes $noise\ RMS \propto \sqrt{MPPC\ current}$
  - Goal: Cross check to see if this relationship is true
- Noise (Pedestal RMS) and Vdrop was measured
  - for a current conveyor gain of 4 using the overvoltage 2V adapter
  - for inputDACs of 10,20,30,40 and 50
  - at temperatures 0, 10, 23 and 30 Celsius.
- Two multimeters measure the voltage drop (Vdrop) across the two irradiated channels
  - Idrop = Vdrop/362 [Ohm]

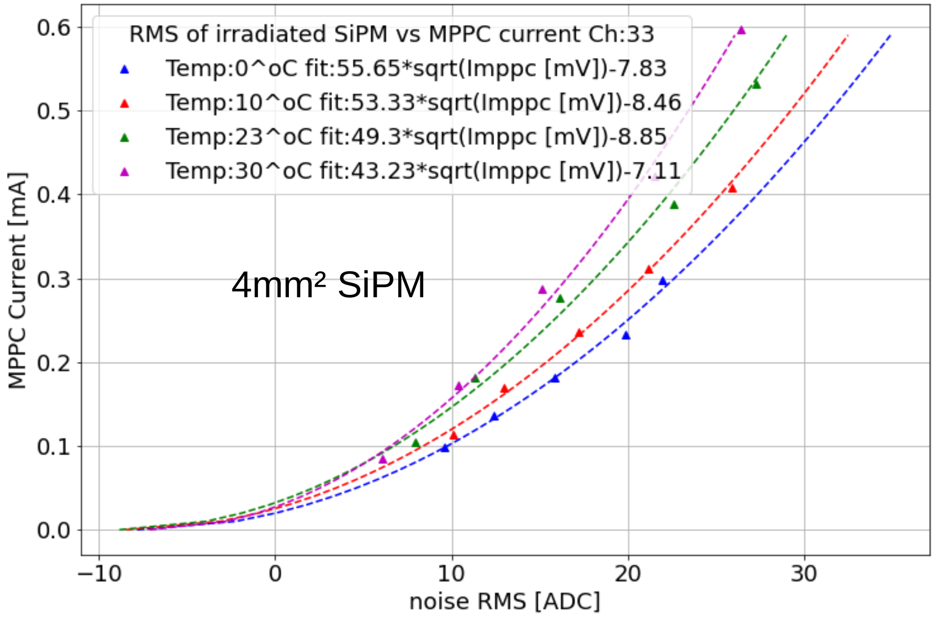


RMS of Irradiated SiPMs

For different temperatures using OV=2V adapter

- An assumption made for the HGCAL's SiPM model is that $noise\ RMS \propto \sqrt{MPPC\ current}$
- This relationship was used to model the plots given below





- **Observation:** The relation between MPPC current and noise seem to be temperature dependant.
- **Possible explanation:** excess noise, after-pulsing etc.
- **Solution:** Look at points at the same overvoltage as the excess noise should be the same for all points : *work in progress*

Summary of the Irradiated SiPM Study

Summary

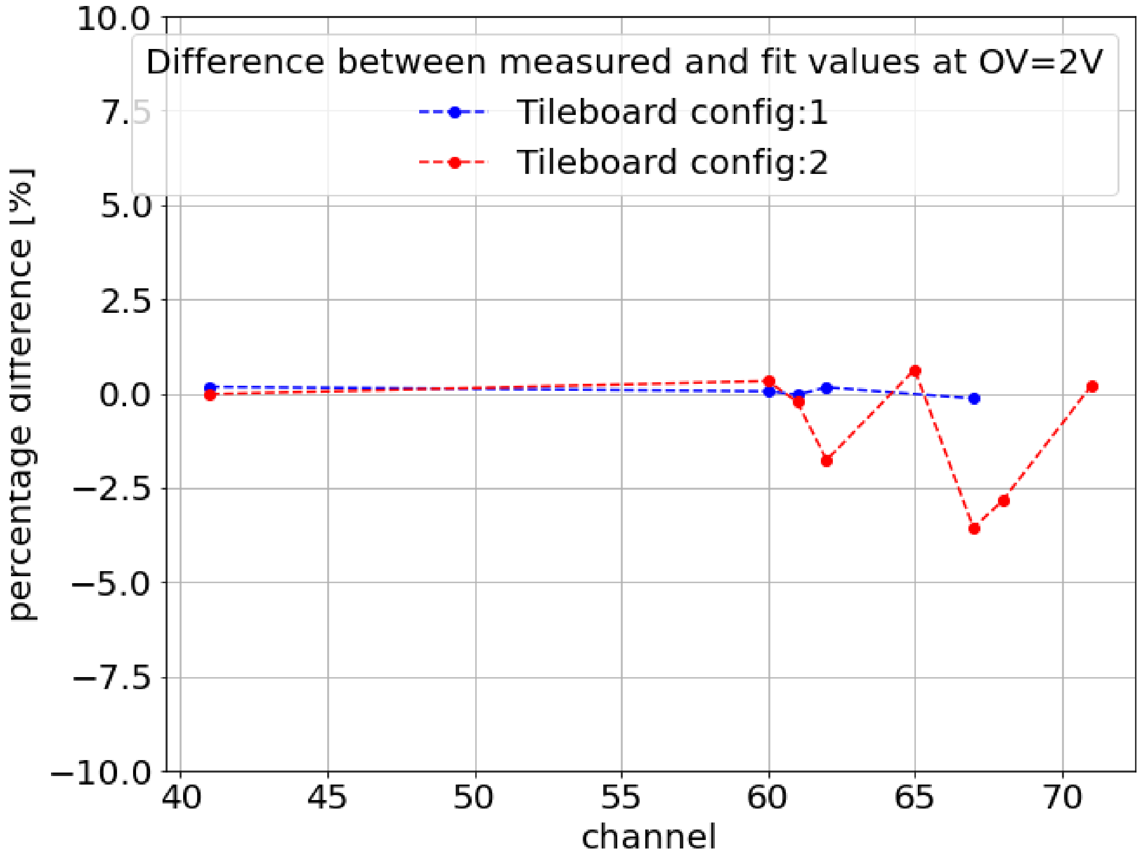
- **Test beam Data:**
  - It might be possible to observe MIP signals from irradiated SiPMs
    - Requires an adaptation of the template fit conditions
    - Has open questions about the noise under the curve
- **Pedestal RMS vs SiPM current Study:**
  - The relation between MPPC current and noise seem to be temperature dependant.
    - Look at points at the same overvoltage
    - Have an additional temperature sensor for precise temperature measurements.

THANK YOU!

BACKUP

BACKUP: Testing the SiPM Gain Correction

For October 2020 test beam data

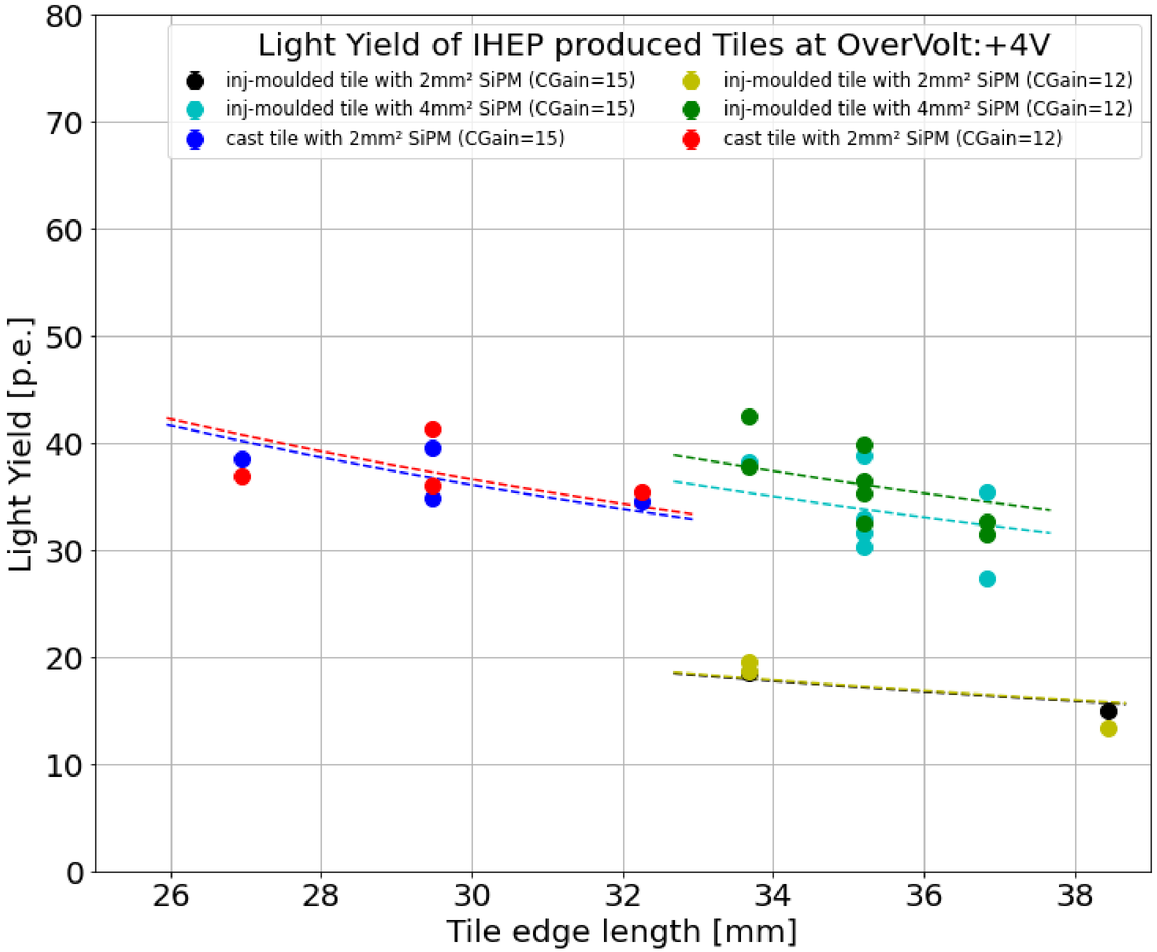


- Since it is possible to measure the SiPM gain of few channels at 2V if conveyor gain 15 is used, it is possible to compare the SiPM gain values from the fit at 2V with the SiPM gain measured at 2V

- If the difference between measured and fit values is taken as a percentage:
  - All fitted values are within <5% of the measured SiPM gains

BACKUP: Consistency with Conveyor Gains

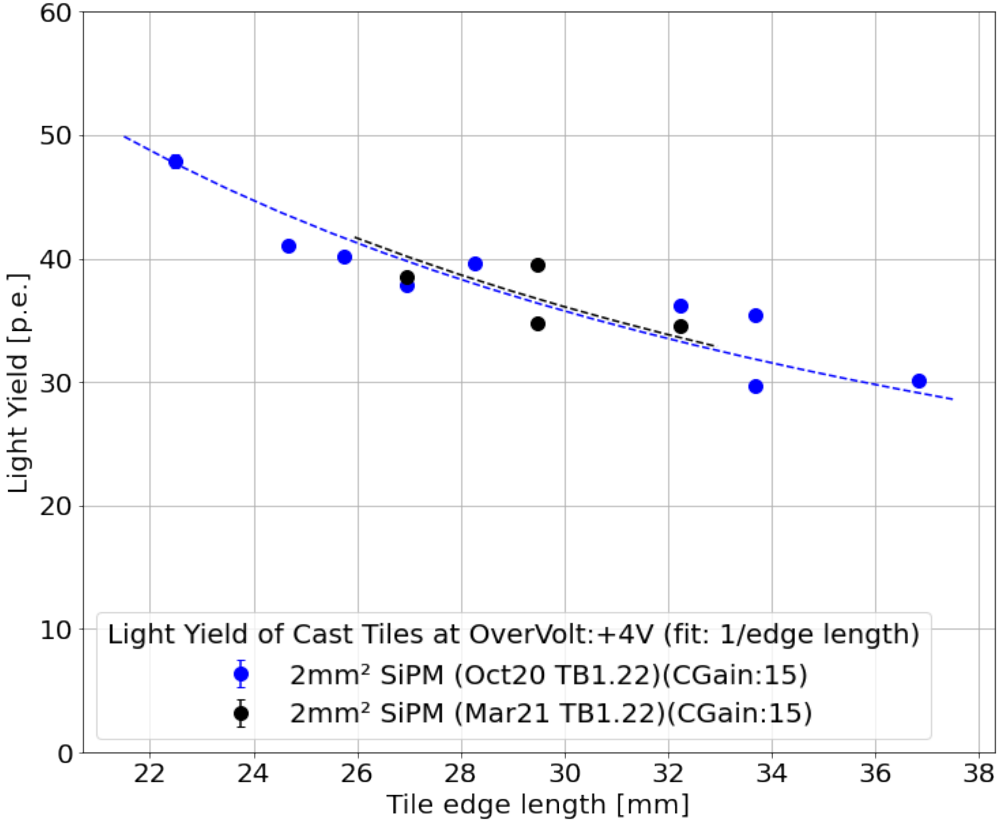
Light Yield of IHEP produced tiles

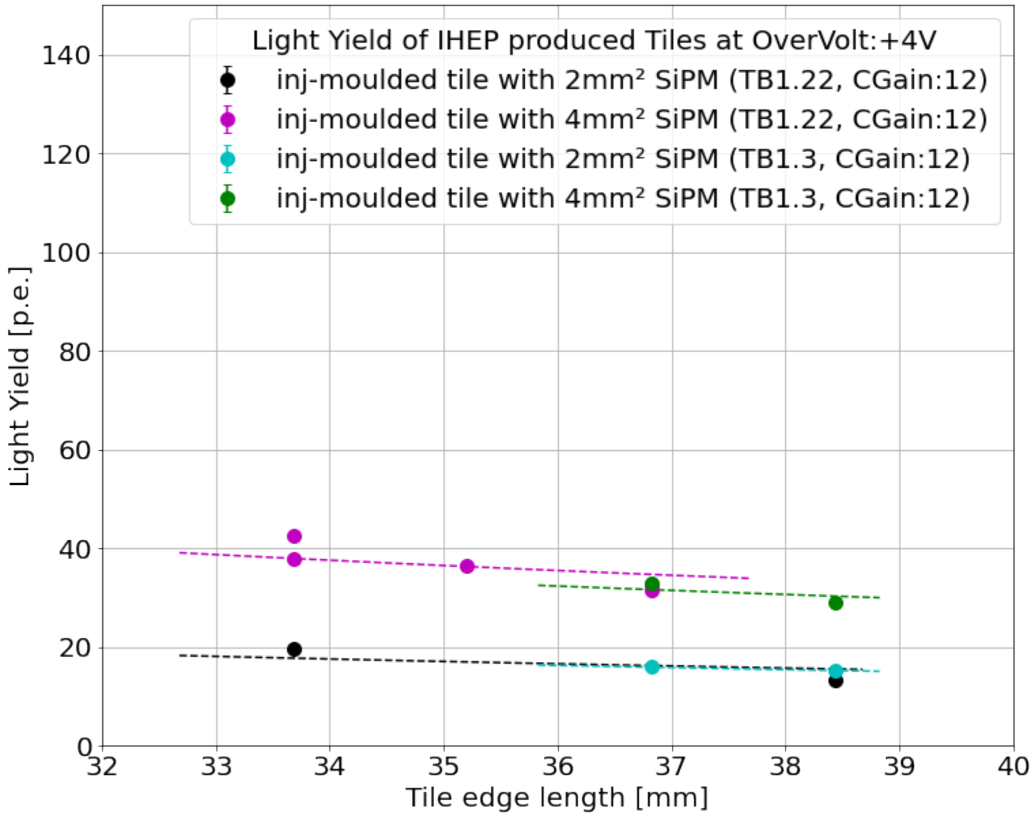


- Conveyor gain affects the SiPM gain and MPV by the same factor.
- As a result, the effect from conveyor gain is canceled out when the light yield is calculated.
- Other consistency checks showed that all results are reproducible between the different tile boards and different test beams (see backup slides).

BACKUP: Reproducibility of Light Yields

For IHEP cast and MEPHI injection-molded tiles



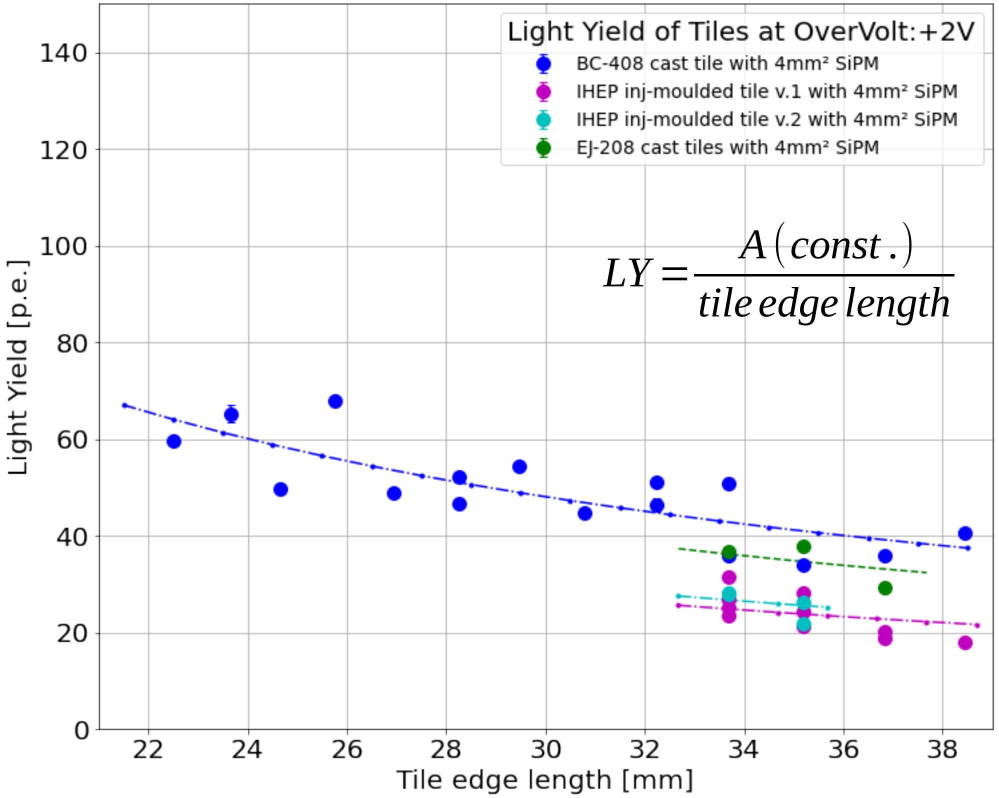


- Light yields measured for the same scintillator tiles at different test beams are similar.
- Similar tiles on the different tileboards also yield similar light yields

BACKUP: Model for Light Yield Measurements for OV=2V

Comparison of light yields with different SiPM sizes and tiles

- Since the results satisfy the basic consistency checks, it is possible to combine the two data sets for 4mm² and 2mm² SiPMs to estimate the final light yields by multiplying light yields of 2mm² SiPMs by 2.06 and using a common fit

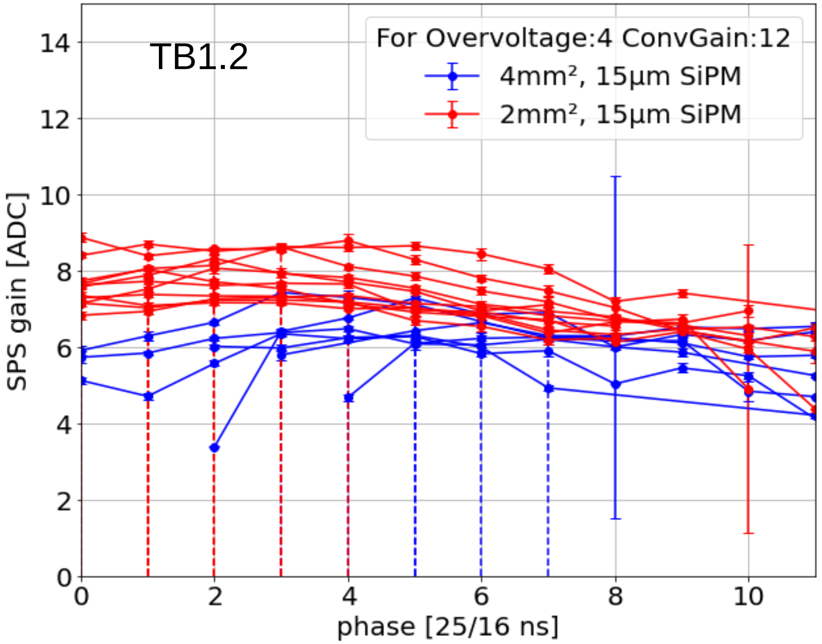


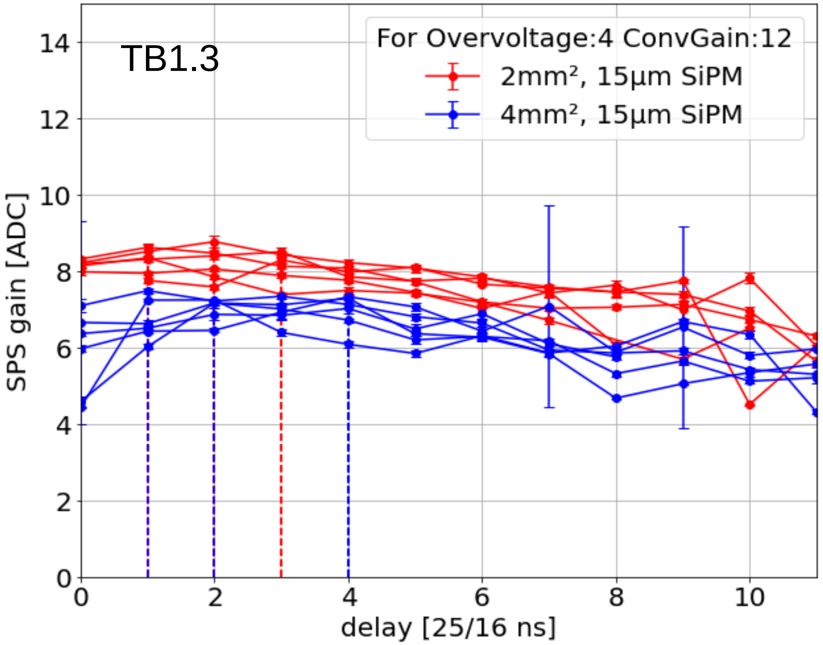
- Ratio comparison of different tiles for OV=2V
  - **IHEP injection-molded (v.2/v.1) = 1.08**
  - **(IHEP injection-molded v.2)/(BC-408 cast) = 0.62**
  - **(BC-408 cast)/(EJ-208 cast) = 1.18**

BACKUP: SiPM Gain Tests via Delay Scans

SiPM gain vs Delay for TB 1.22 and TB1.3

- SPS data for TB1.2 and TB1.3 were taken in order to re-evaluate the SiPM gains measured at the test beam



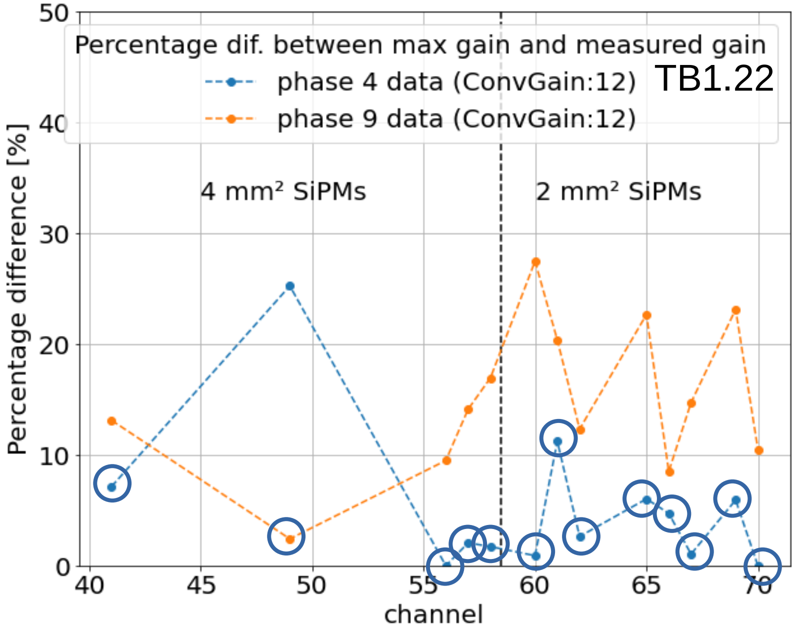


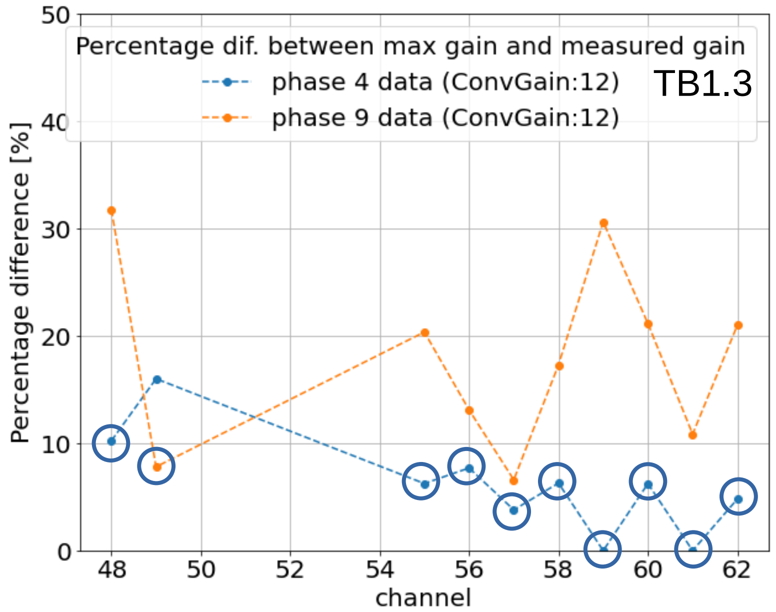
- Not all channels peak at the same point.
  - TB1.3 : Most channels peak at or around phase=3
  - TB1.2 : Some channels peak around phase=3 and some around phase=6.

BACKUP: Percentage Difference based SiPM Gain Correction

Factor by which the gain measured at phase 4 or 9 varies from the actual gain

- Only phases 4 and 9 were measured at the test beams since October 2020
  - Deviation of measured gain from SiPM gain in most channels is below 10%





- Based on this study we can correct SiPM gain to obtain the maximum since we know the two values for phase=4 and phase=9:

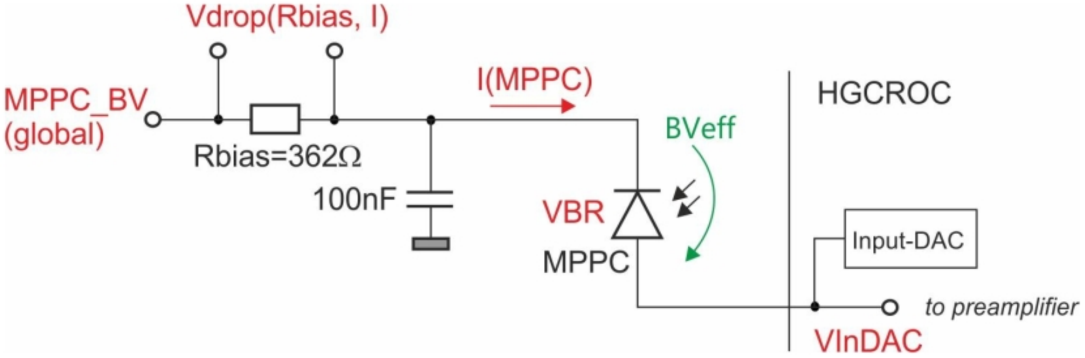
$$M = m + \frac{m \times d}{100}$$

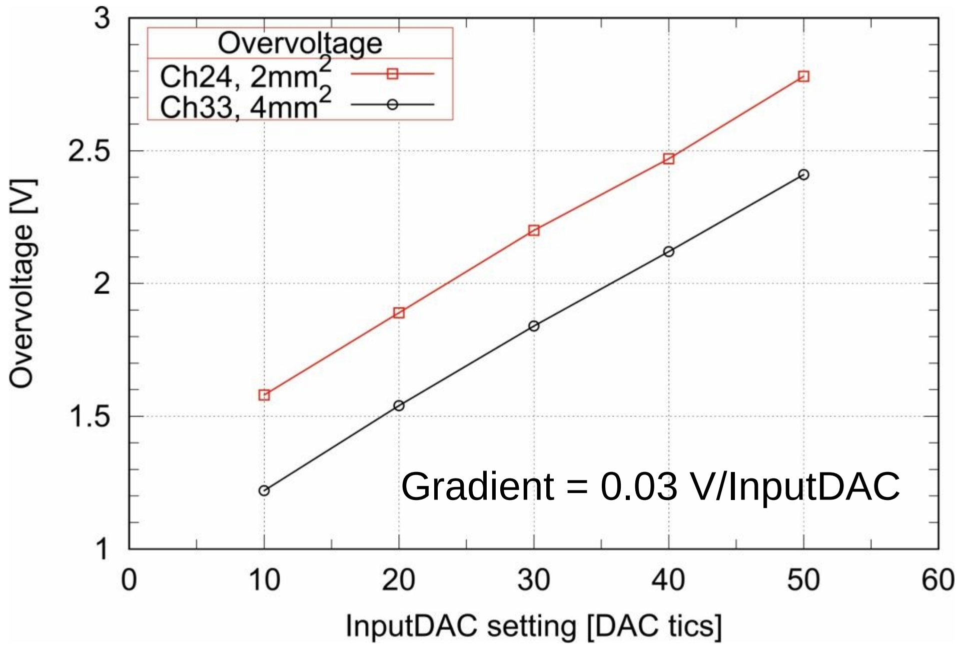
Where:
M = Actual SiPM gain
m = Measured SiPM gain at phase 4 or 9
d = Percentage difference between SiPM gain and gain measured at phase 4 or 9 in lab

Overvoltage calculation in Irradiated SiPMs

From Mathias Reinecke's slides (Oct 12th 2021)

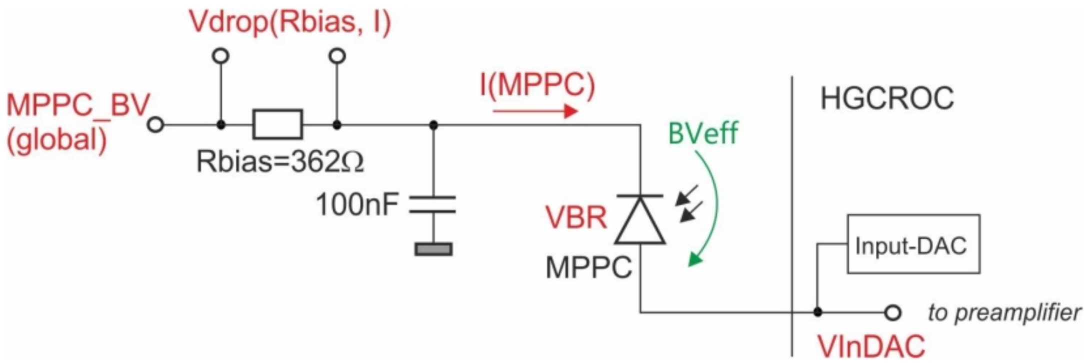
- The effective bias voltage **BVeff** of each MPPC depends on the global **MPPC_BV**, the voltage drop in the bias resistor from the MPPC current **Vdrop** and the Input-DAC voltage **VinDAC**.
- Vdrop only becomes relevant for irradiated MPPCs with high dark-count rate DCR (-current) OR at very high signal rates.
- For the MPPC overvoltage (OV) also the individual breakdown voltage **VBR** of the MPPC needs to be considered.
- VBR is also dependant on temperature (**Vtemp**)
- Therefore overvoltage can be calculated as:
  - OV = MPPC_BV – Vdrop – VInDAC – (VBR – Vtemp)
- The MPPC overvoltage has been determined by measuring MPPC_BV, Vdrop and VinDAC for the irradiated MPPCs on TB1.2_2 and different InputDAC settings.





Overvoltage of Irradiated SiPMs for different temperatures

Using the Climate Chamber



- Using the equation:

  OV = MPPC_BV – Vdrop – VInDAC – (VBR – Vtemp)

- where : VInDAC = 0.03*(31-InDAC [ADC])
  Vtemp = 0.035*(23-Temp [°C])
  VBR taken from Hamamatsu data sheet

  the overvoltage of all data points were corrected

- Resulting variation of MPPC current with overvoltage can be modeled using an exponential function from which the MPPC current vs temperature can be calculated for a fixed overvoltage.