Studies of Irradiated SiPMs with CMS HGCAL Tileboards

Latest Tests of the CMS HGCAL Tileboard Prototypes

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High Granularity for the High Luminosity LHC

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

- HL-LHC will integrate **ten times more luminosity** than the LHC

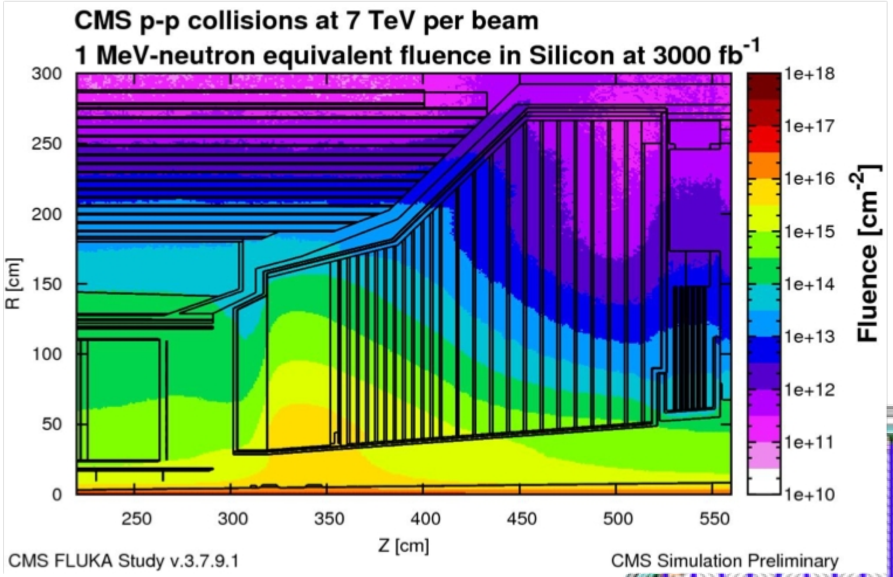
- This poses significant challenges for radiation tolerance and event pileup on detectors

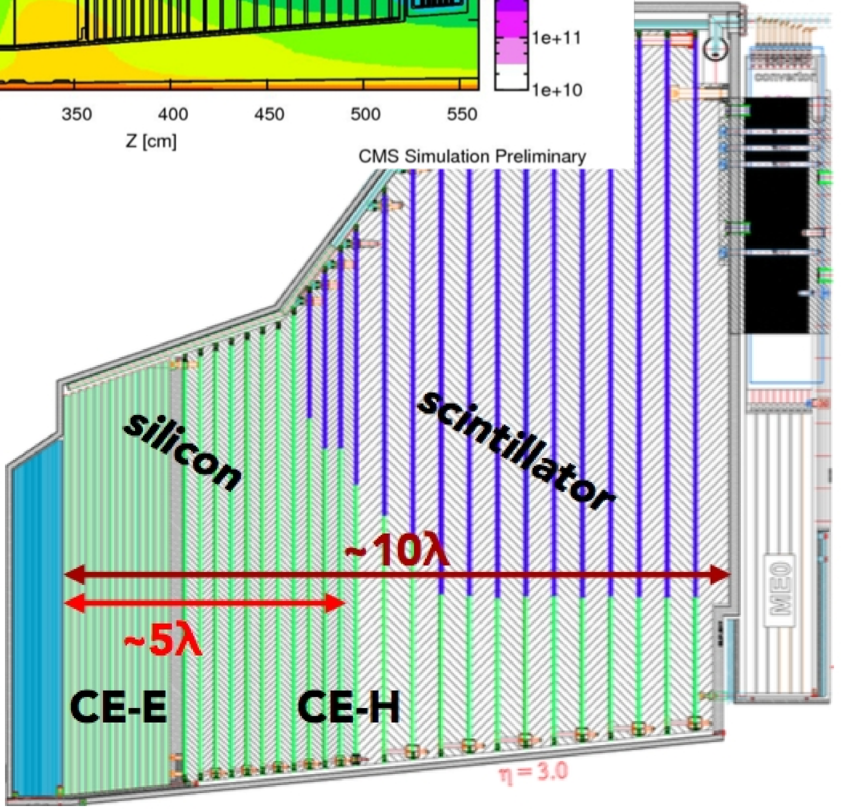
- Need to replace the ECAL crystals and HCAL scintillators of the CMS end cap calorimeter

- Proposed detector: a **5D (imaging) calorimeter using particle flow**

- The active area of CMS endcap calorimeter (HGCAL) will consist of:
  - silicon detector section
  - **scintillator section**

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

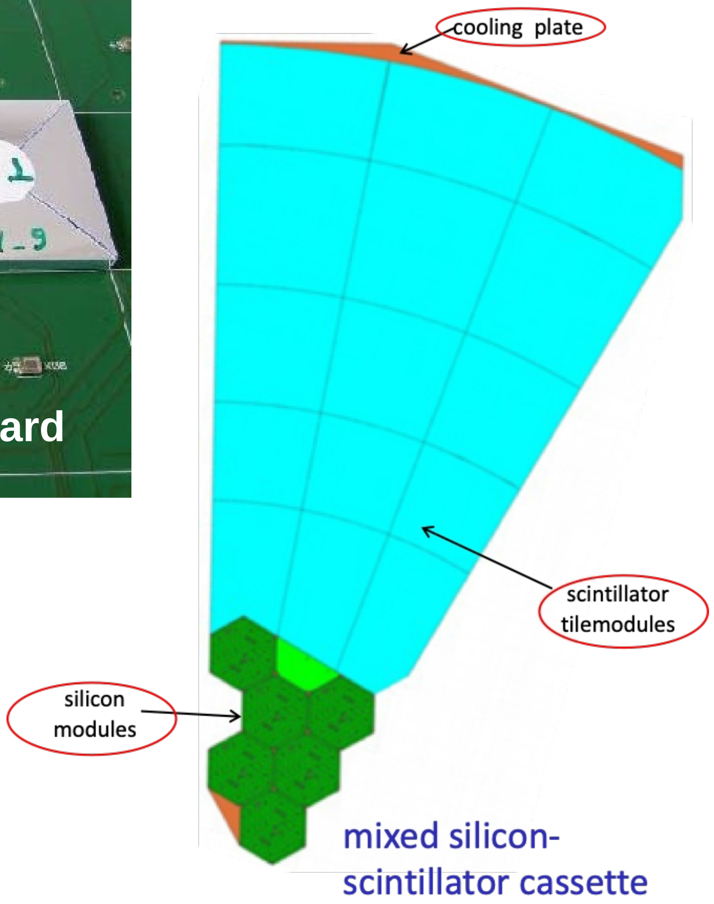




Scintillator Component of the Hadronic Endcap Calorimeter

CMS HGCAL Tileboard and Front-End Electronics

- SiPM-on-tiles consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)



Scintillator Component of the Hadronic Endcap Calorimeter

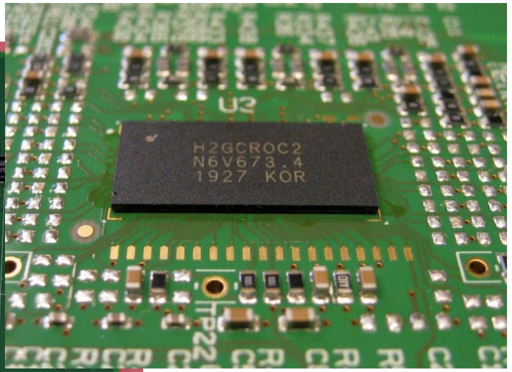
CMS HGCAL Tileboard and Front-End Electronics

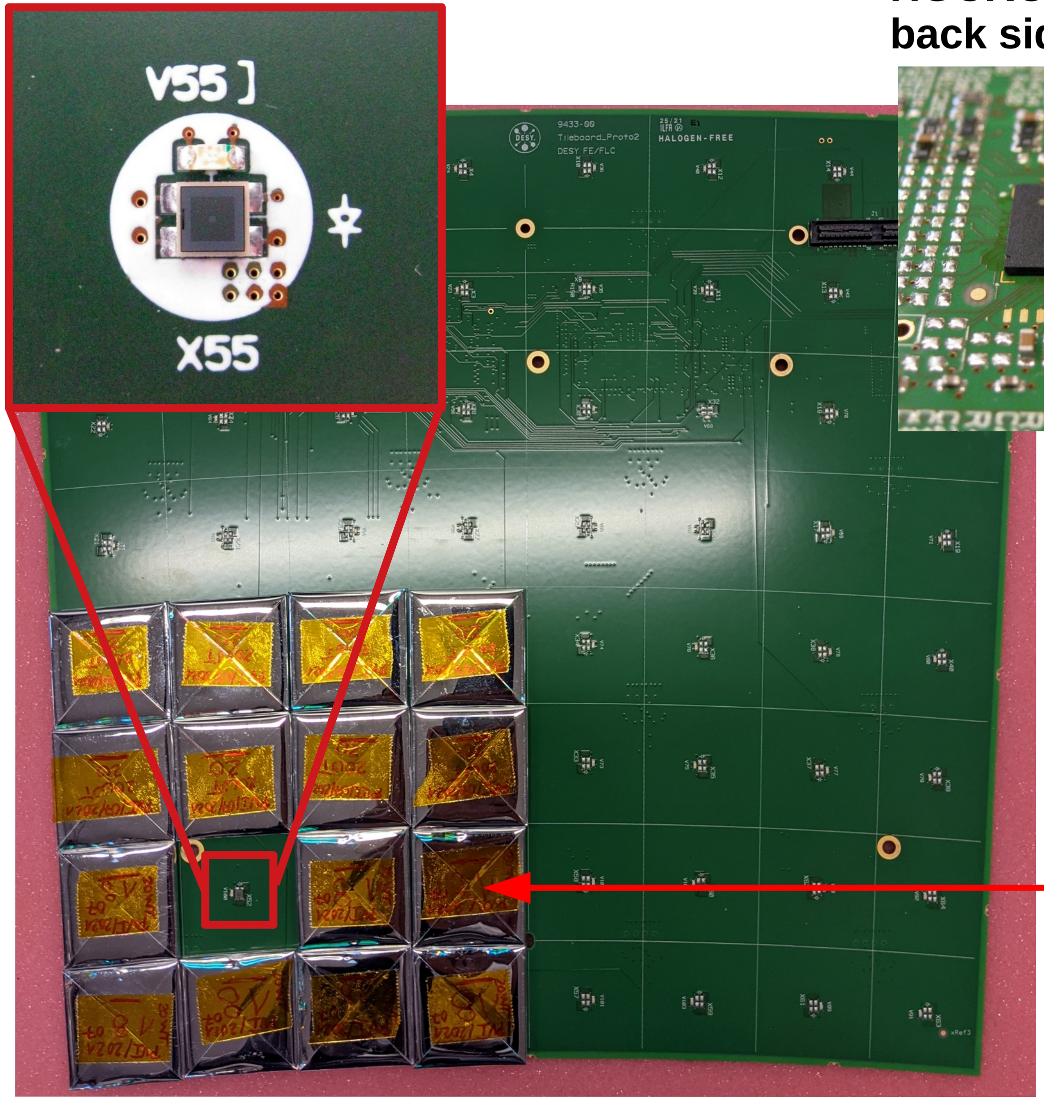
- SiPM-on-tiles consist of individually wrapped plastic scintillator tiles placed on silicon photomultipliers (SiPM)

- The signals from SiPM-on-tiles are read out by the HGCROC front end electronic ASIC
    - **ADC scale for lower gains**
    - Time over Threshold (TOT) for higher gains
    - Time of Arrival (TOA) for timing information

- Tileboards hold the SiPMs, scintillators, on-board electronics and LED system

HGCROC(V2) on the back side of the tileboard





Scintillator tiles on the front side of the tileboard

Tests with Irradiated SiPMs

Motivation

- Response of each SiPM-on-tile cell on the energy scale will be calibrated using the MIP signal
  - Radiation damage decreases scintillator light output and increases the SiPM dark current induced noise
  - **Important to predict the noise of irradiated SiPMs** including effects of read-out electronics (such as shaping or effective integration time)

- Irradiated SiPMs provide data on how the pedestal noise and current increase with accumulated neutron fluence

Tests with Irradiated SiPMs

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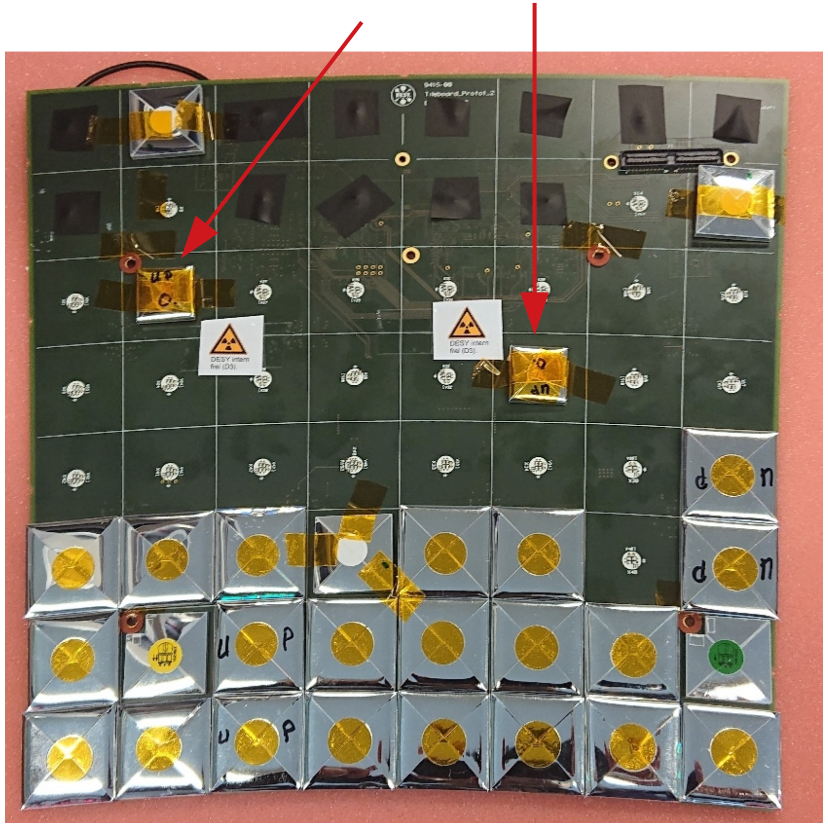
  - **Important to predict the noise of irradiated SiPMs** including effects of read-out electronics (such as shaping or effective integration time)
- Irradiated SiPMs provide data on how the pedestal noise and current increase with accumulated neutron fluence
- Use tileboard TB1.2 to establish relation between current and noise
  - Contains **Hamamatsu HDR-2 SiPM of 2 mm² and 4 mm²** active area each with a **15µm pitch** and custom radiation hard packaging.
  - **Irradiated to a fluence of 2×10^{12} n/cm² at room temperature** (Dark current at overvoltage=2V equivalent to expected end-of-life fluence at -30°C)

Irradiated MPPCs with R0 cast tiles



Relationship between Noise and Current passing through SiPM

Theoretical Background

- When using different temperatures (or light intensities) to vary SiPM noise for a fixed overvoltage, the current also increases as a function of SiPM noise

  - For a SiPM with negligible excess noise factor caused by after-pulsing and crosstalk

$$I=\frac{N\cdot G\cdot e}{\Delta t}$$

where I = current through SiPM
N = no. of fired pixel in time Δt
G = SiPM gain
e = electron charge
Δt = time period

  - $$Q=\int I\cdot dt=N\cdot G\cdot e$$ where Q = charge collected by SiPM

  - Since the noise scales as a function of $\sqrt{N}$:

$$noise\ RMS=\sqrt{N}\cdot G\cdot e=\sqrt{I}\cdot\sqrt{G\cdot e\cdot\Delta t}$$

  - That is, for a given overvoltage: $$noise\ RMS\propto\sqrt{SiPM\ current}$$

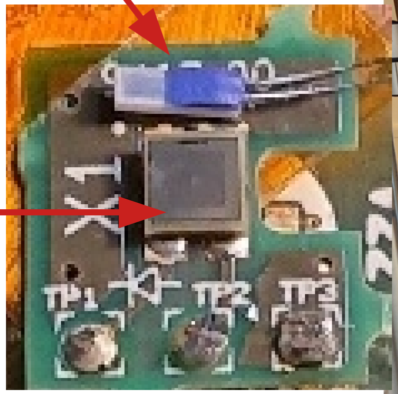
Setup for the Measurement of SiPM currents

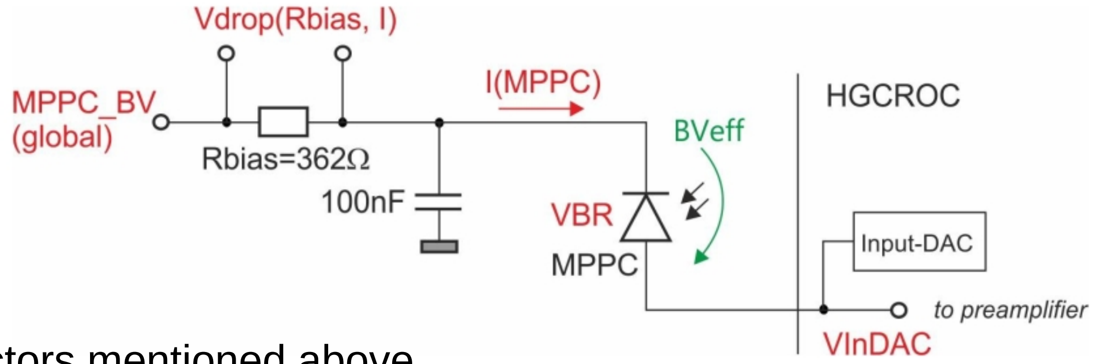
With Climate Chamber

- The tileboard with the irradiated SiPMs is set up inside the climate chamber
- **Inputs:**
  - Fixed bias voltage **(MPPC_BV)** of 41.6V
  - InputDAC parameter of HGCROC is used for finer bias voltage variations by up to +/- 0.5V **(Vindac)**
  - Temperature of climate chamber is changed between -30°C and 30°C
- **Measurements:**
  - Current flow **(Imppc)** across the irradiated SiPMs
  - **Temperature** of the SiPM (using PT1000 sensors 1 mm away from SiPMs)
  - Pedestal mean and noise (RMS) in ADC counts
- **Overvoltage (OV)** is then calculated by taking into account all the factors mentioned above

PT1000 temperature sensor

Irradiated SiPM (MPPC)

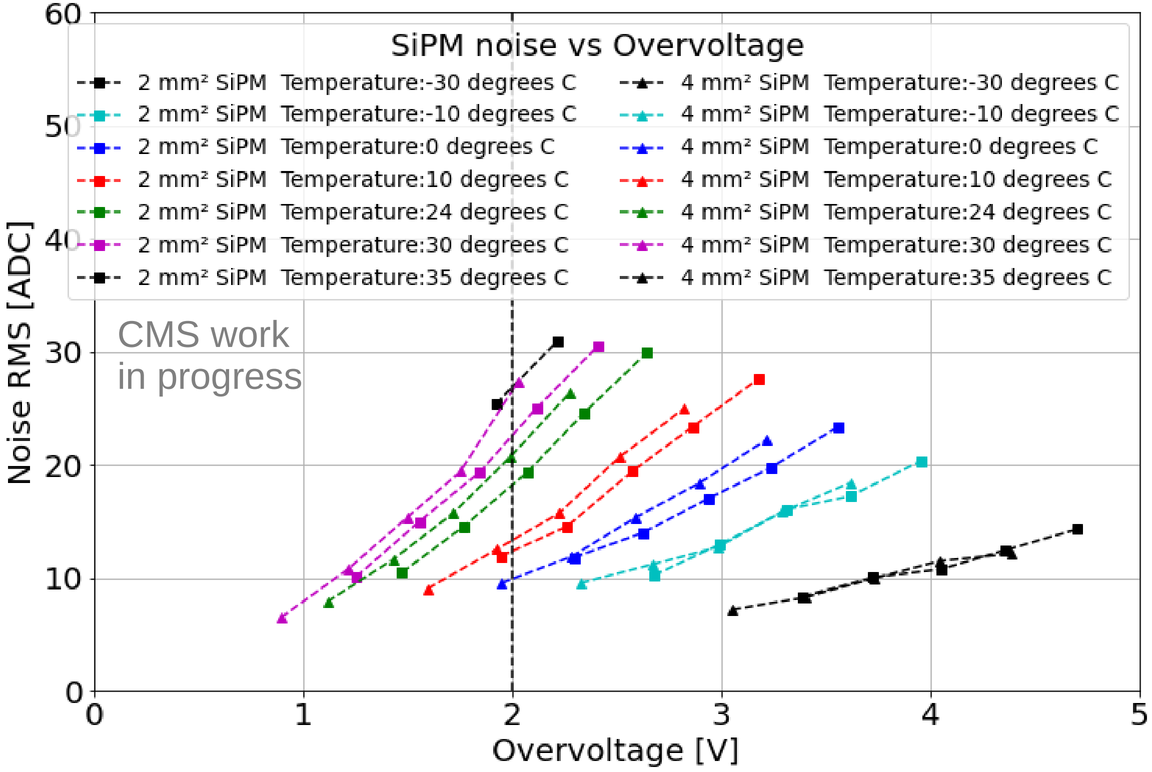


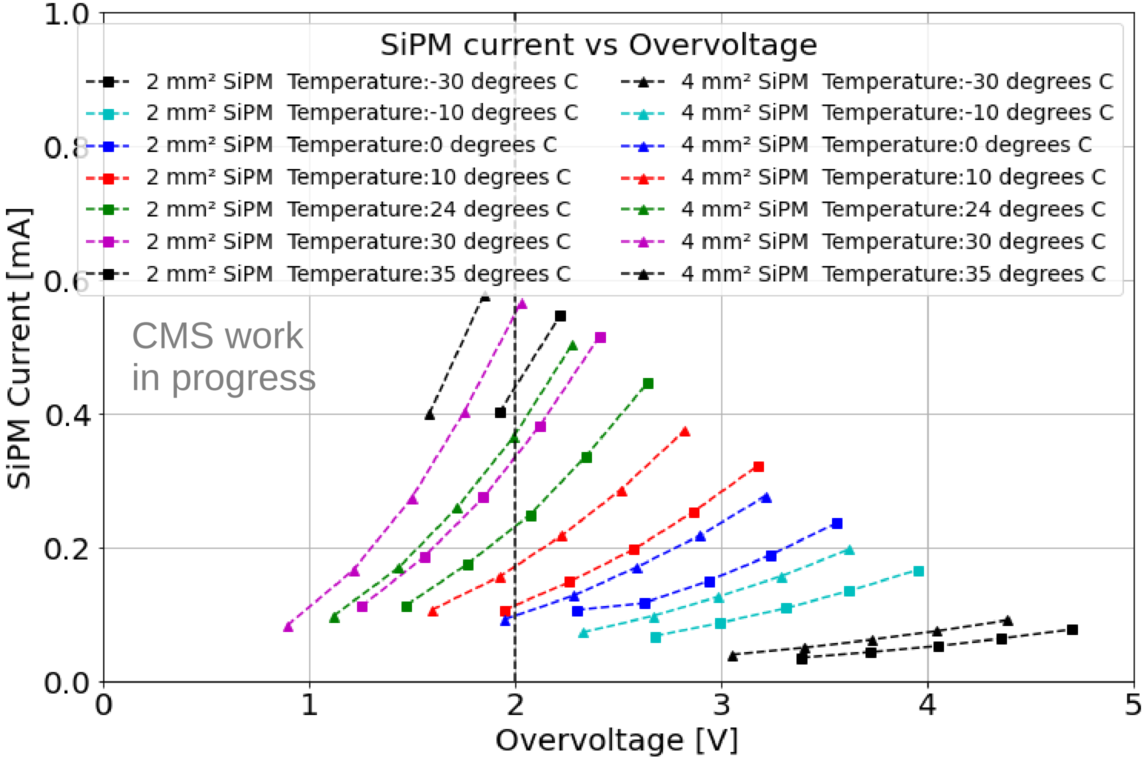


Overvoltage of Irradiated SiPMs for different temperatures

Using overvolatage=2V adapter board

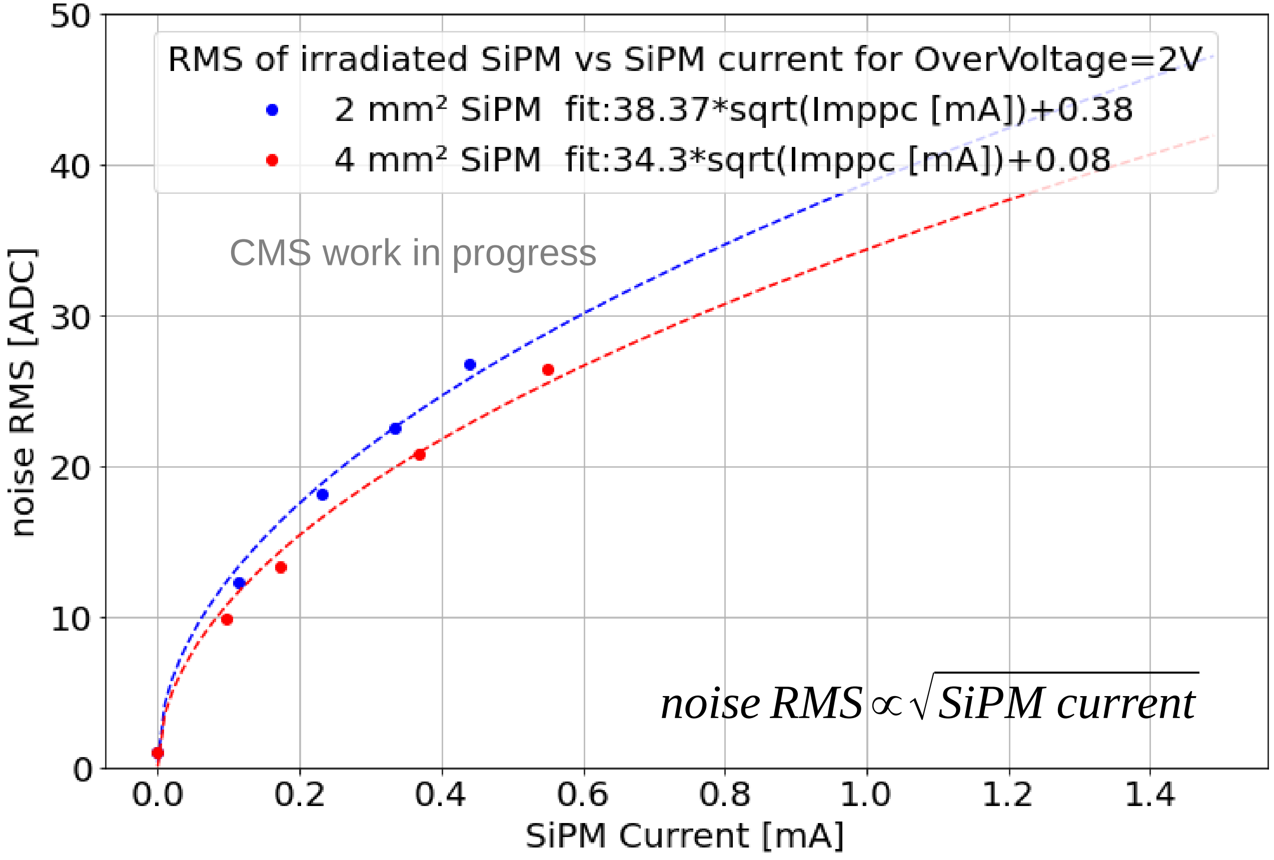
- One can sample points along an overvoltage of 2V in order to compare the corresponding noise level expected from a certain MPPC current:
  - Take points just before and after the overvoltage value required and use a linear interpolation to calculate value at overvoltage





Direct comparison of SiPM current and Noise RMS

at OV = 2V



- Currents passing through SiPMs of different sizes should affect the noise in a similar way
- This means that the noise levels should be same too
  - This is not seen in the results
- **Possible explanation:**
  - Temperature changes the internal working conditions of the SiPM (eg: change in excess noise factor)
  - Different effective integration times due to different pulse shapes (as a consequence of different device capacitance)
  - Unequal irradiation of the two SiPMs : highly unlikely

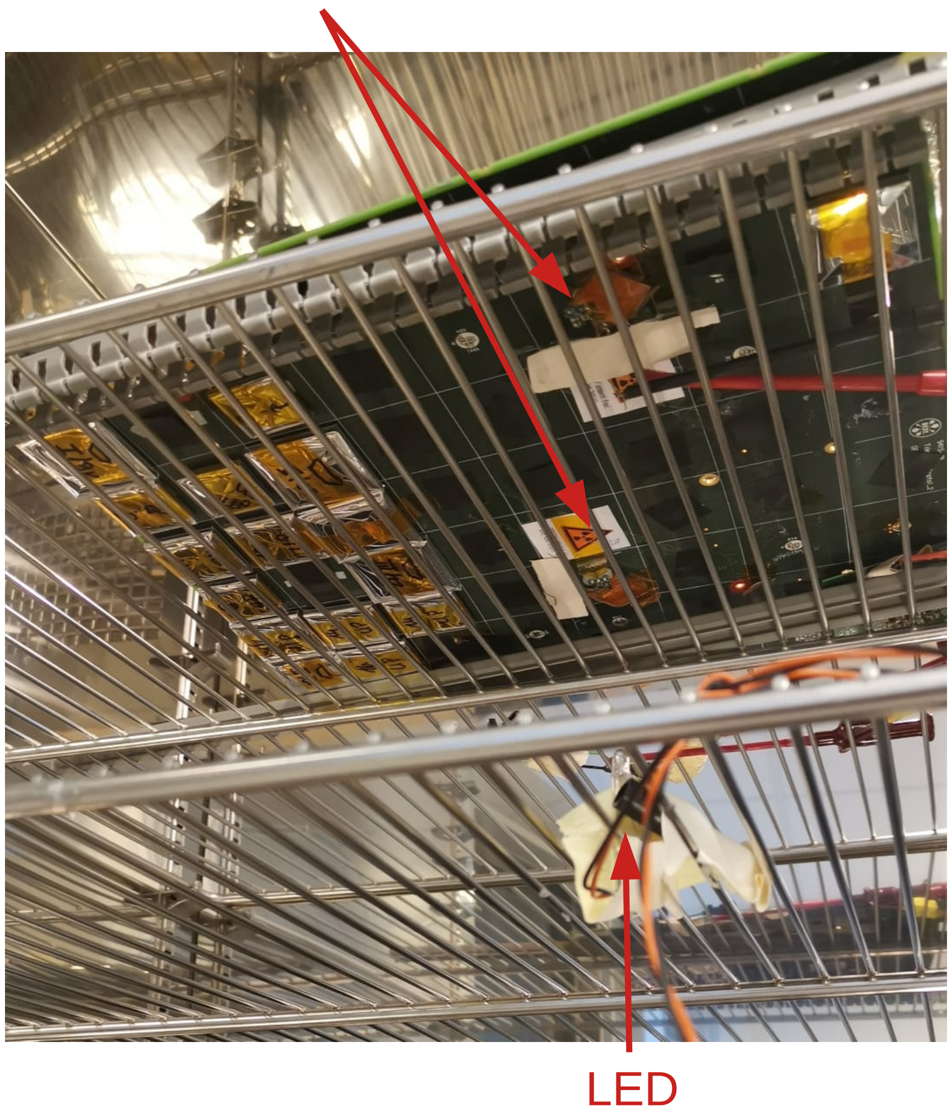
Setup for the Measurement of MPPC currents

Using an externally mounted LED

- In order to understand if the temperature change caused the change in SiPM conditions, an alternative setup was developed

- **Methodology:**
  - Tileboard is placed in a black box
  - A constant light emitting LED was mounted underneath the irradiated channels on the tileboard
  - The intensity of the LED can be varied by changing the voltage given to the LED

- The experiment was conducted at 25°C at an overvoltage of ~2V



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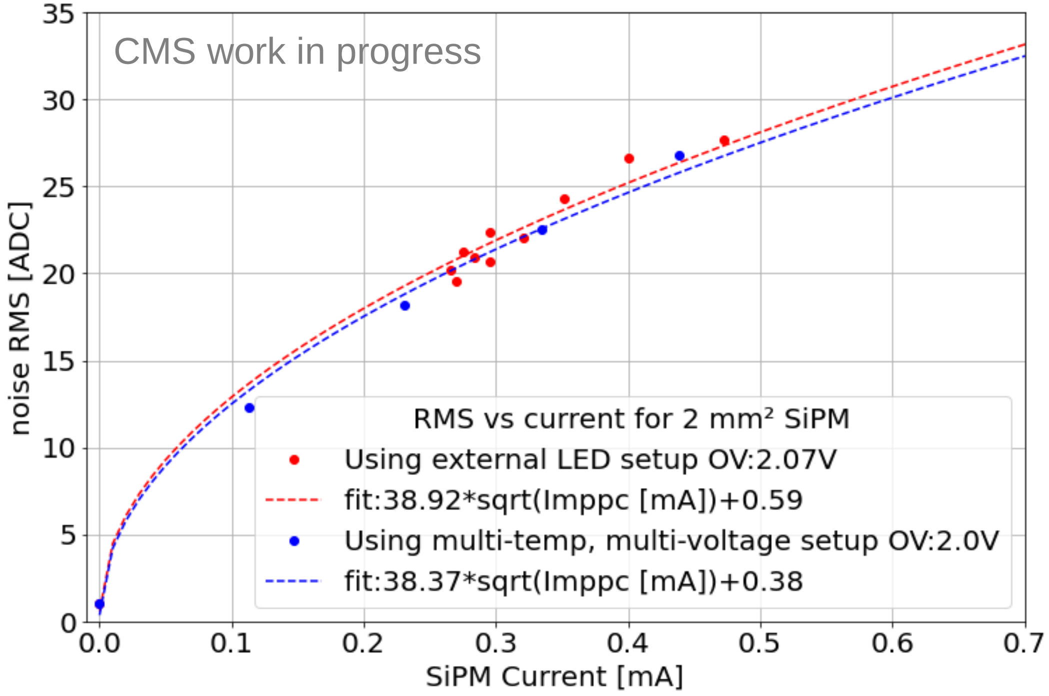

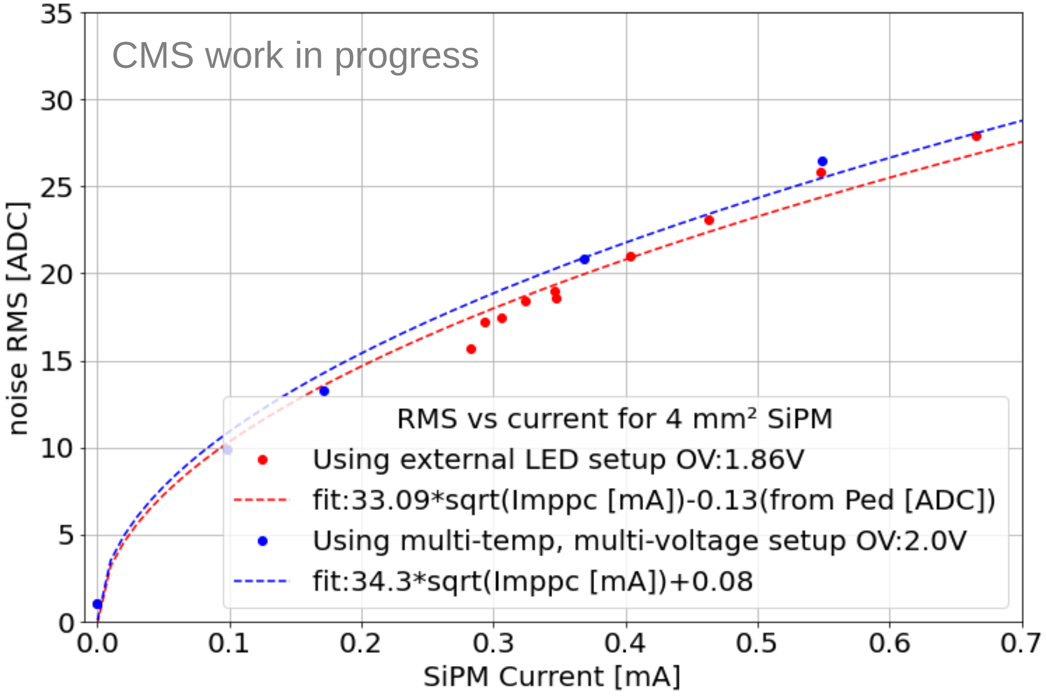

- The two independent setups yield very similar results
  - Effects from the changes in excess noise factor is negligible
- Noise vs current relationship seem to depend on the SiPM size
  - **Remaining possible explanation:** different effective integration times due to different pulse shapes

Summary

Studies of Irradiated SiPMs with CMS HGCAL Tileboards

- SiPM-on-Tile technology developed by the CALICE collaboration is being applied as part of the HGCAL upgrade
- In order to verify the relationship between the current passing through an irradiated SiPM and the pedestal noise (RMS), two setups were used
  - Using the change in overvoltage with temperature and InputDAC parameter of the HGCROC to obtain the data
  - Using an constantly illuminated LED to obtain the data
- Both methods yield the same relationships
  - For a given SiPM at a fixed overvoltage of a certain size, $noise\ RMS \propto \sqrt{MPPC\ current}$ holds true
  - SiPMs of different sizes however see different curves
    - Could be due to the differences in effective integration times due to different pulse shapes between the two SiPMs

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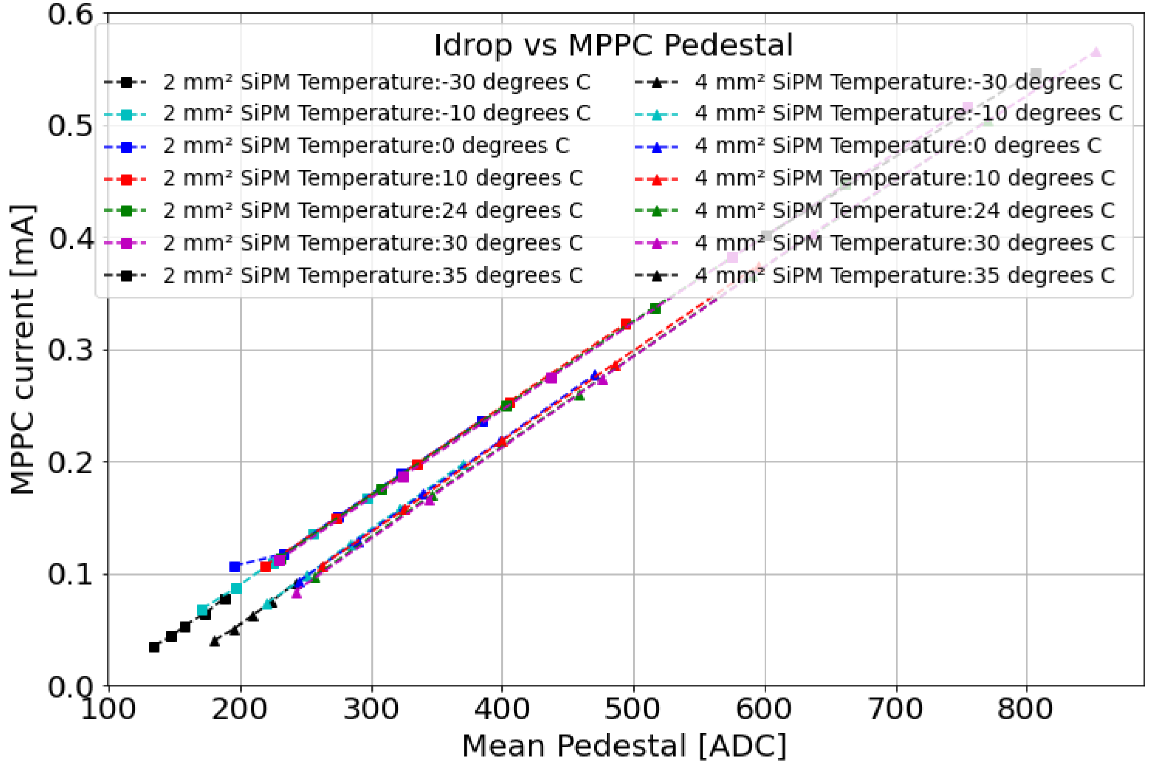
THANK YOU FOR YOUR ATTENTION!

BACKUP

Comparison SiPM current and Pedestal

Using data from irradiated SiPMs

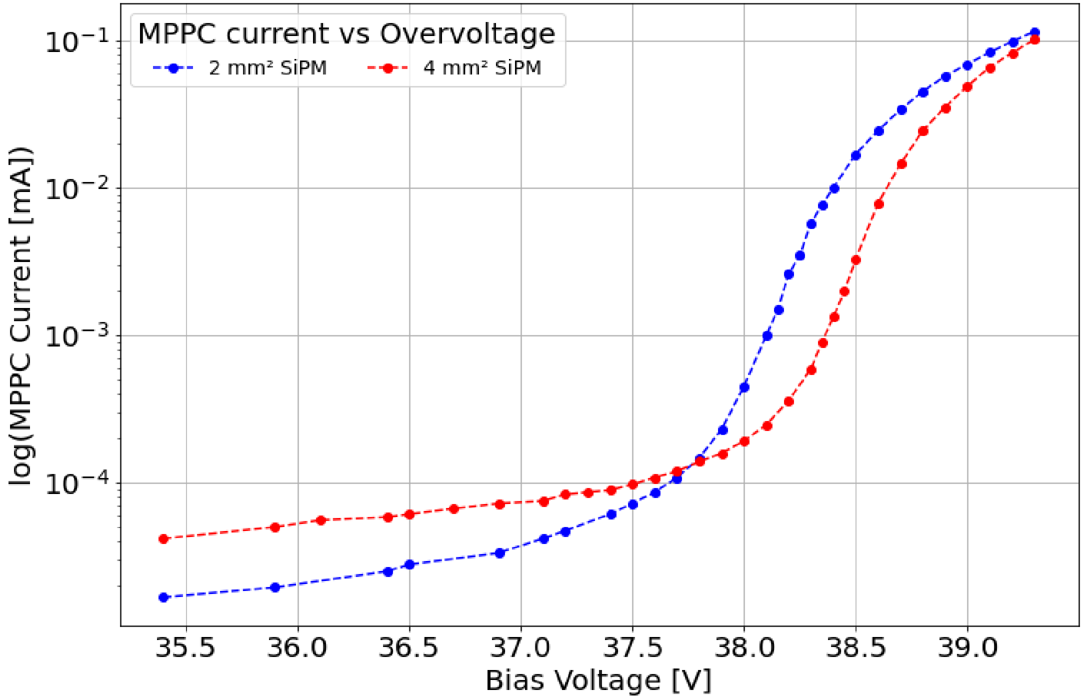


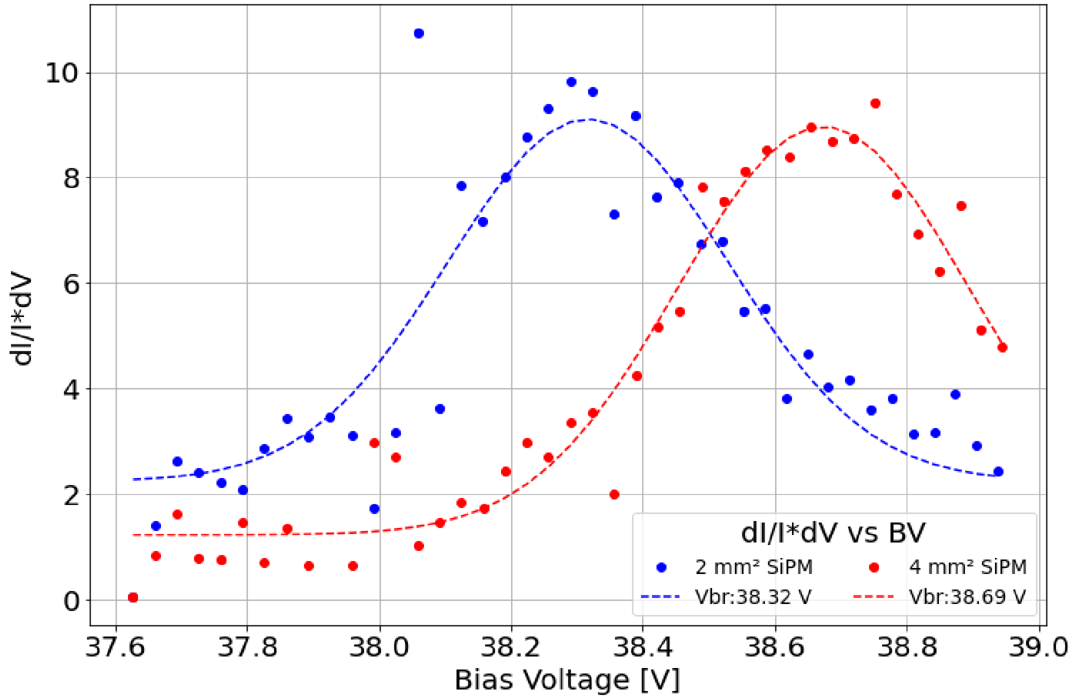
- Plot compares current passing through SiPM and mean calculated from pedestal.
- Both measure the current before and after DC-DC conversion
  - Relationship must be linear regardless of the temperature and overvoltage
  - For a given SiPM with fixed HGCROC parameters, it is possible to use the pedestal values as an alternative for SiPM current

Breakdown Voltage Determination with Irradiated SiPMs

I-V curves for irradiated SiPMs

- Breakdown voltages used so far were Hamamatsu measured voltages before irradiation
- Goal: See if the voltage measured via I-V curve for irradiated SiPM is similar to the Hamamatsu measured value



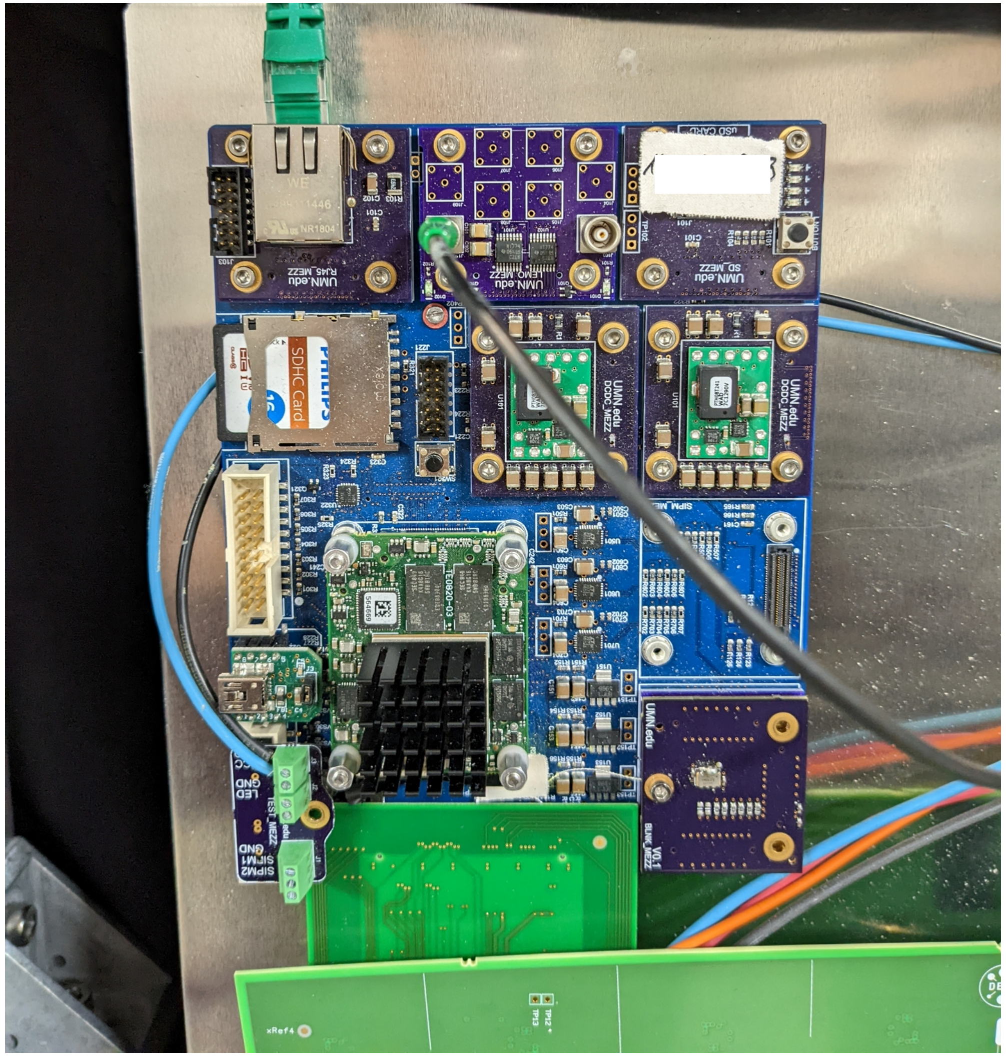


- Hamamatsu measured Vbr : for 2mm² SiPM = 37.82 V (–0.50V) for 4mm² SiPM = 38.16 V (–0.53V)
- 0.5V difference was expected due to differences in Vbr definitions and measuring methods

OUTLOOK: Tileboard Tester Data Acquisition System

Introduction

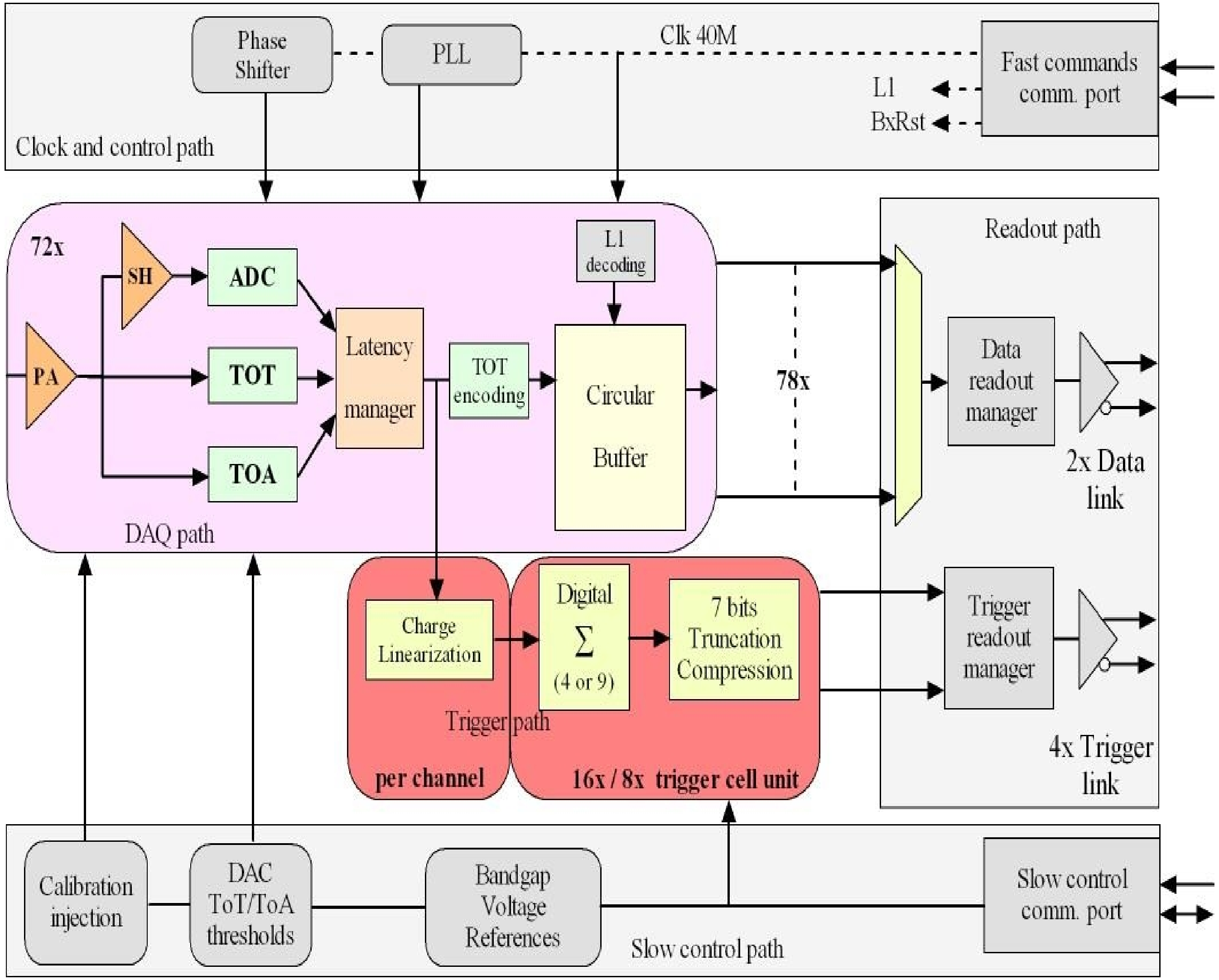
- Data acquisition by a Xilinx Zynq-based module custom-produced to communicate with the tileboards (tileboad tester DAQ)
  - Parallel data taking and readout in final CMS/LHC rate
  - Sends necessary commands needed to
    - Adjust and read voltages including the SiPM bias voltages.
    - Read the outputs from the PT1000 temperature sensors on board the tileboards
    - Configure the HGCROC necessary for data acquisition
  - Raw data is saved as a .raw file and a ROOT file alongside a log file containing the outputs of all slow control parameters such as on-board voltages and temperatures.
  - Has opened the possibilities for simultaneous data taking from multiple tileboards
    - **Possible applications:** cosmic test stand or a stack for shower studies at testbeams



HGCROC(v2) Front End Read Out ASIC

Introduction

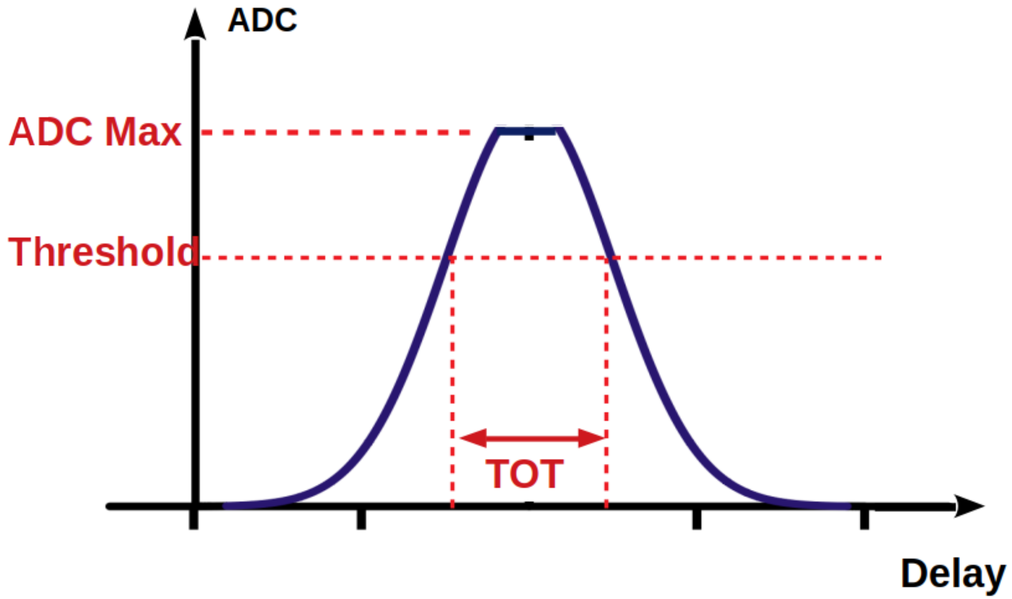
- HGCROC(v2): Latest prototype of the front end read out ASIC to be used in the CMS HGCAL
  - CMOS 130 nm (TSMC) technology
- Two versions:
  - Silicon version: HGCROC
  - **SiPM version:** H2GCROC
    - Additional current conveyor for amplification
- Integrates up to 72 channels to read out
- Measurements:
  - Charge:
    - **ADC (Pulse Amplitude)**
    - Time over Threshold (TOT)
  - Timing:
    - Time of Arrival (TOA)

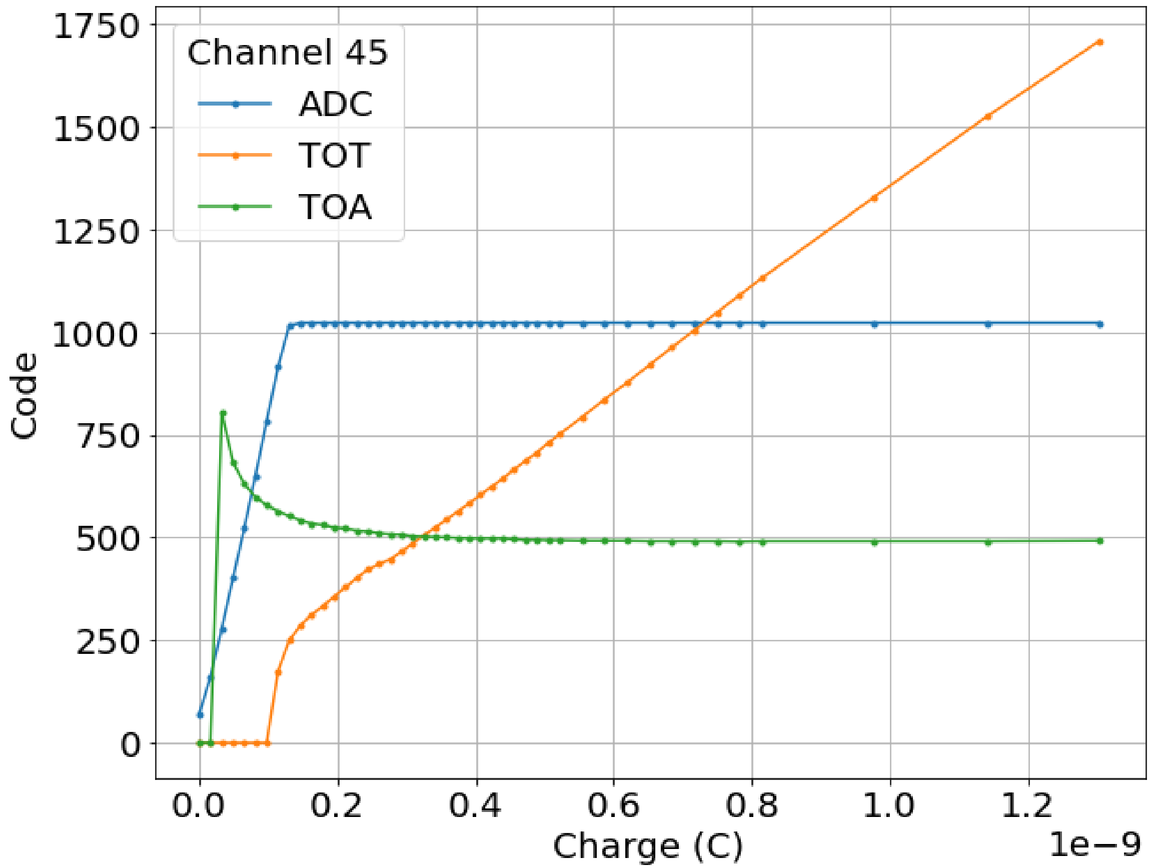


Charge Measurement with HGCROCv2

Low and High Gain Modes

- Pulse amplitude before saturation: ADC measurement
- Pulse amplitude after saturation : TOT measurement



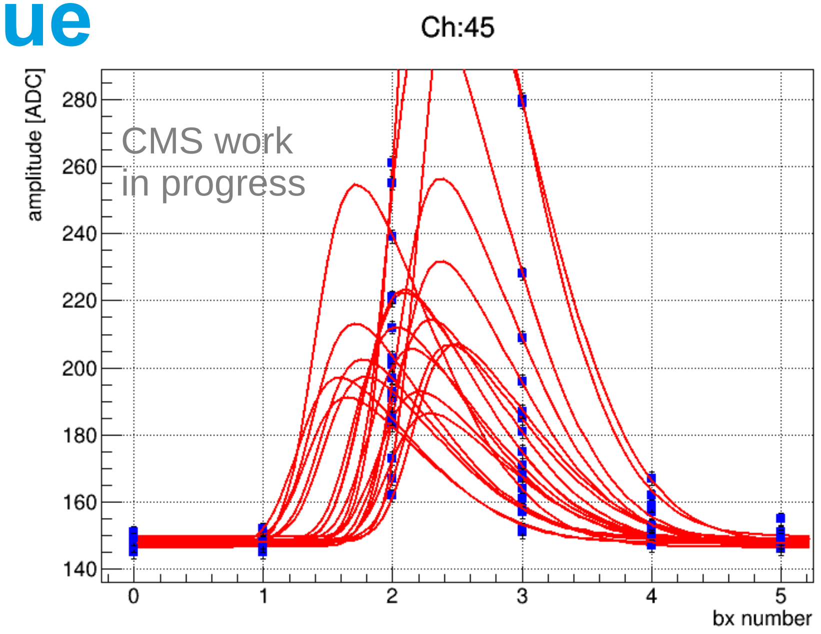


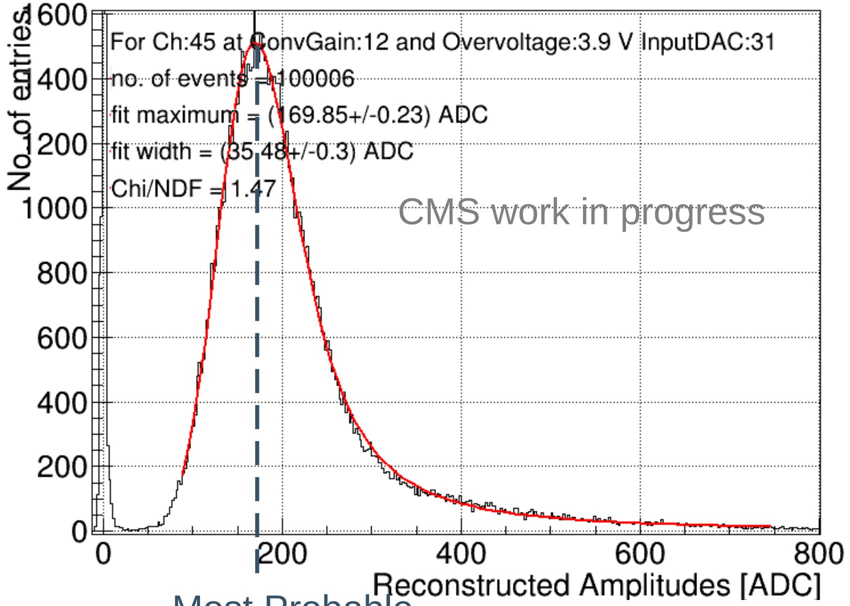
Measurement using external charge injection into the HGCROC channel 45

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 need to be extracted offline
- Pulse amplitude is reconstructed using an **event-by-event template fit to multiple samples**
  - 6 points sampled at 25 ns rate per event are fitted using a **skewed-Gaussian fit with fixed std. dev. and skewness.**
- The **most probable value (MPV)** is extracted from the resulting pulse amplitude spectra using a fit of a Landau distribution convoluted with a Gaussian

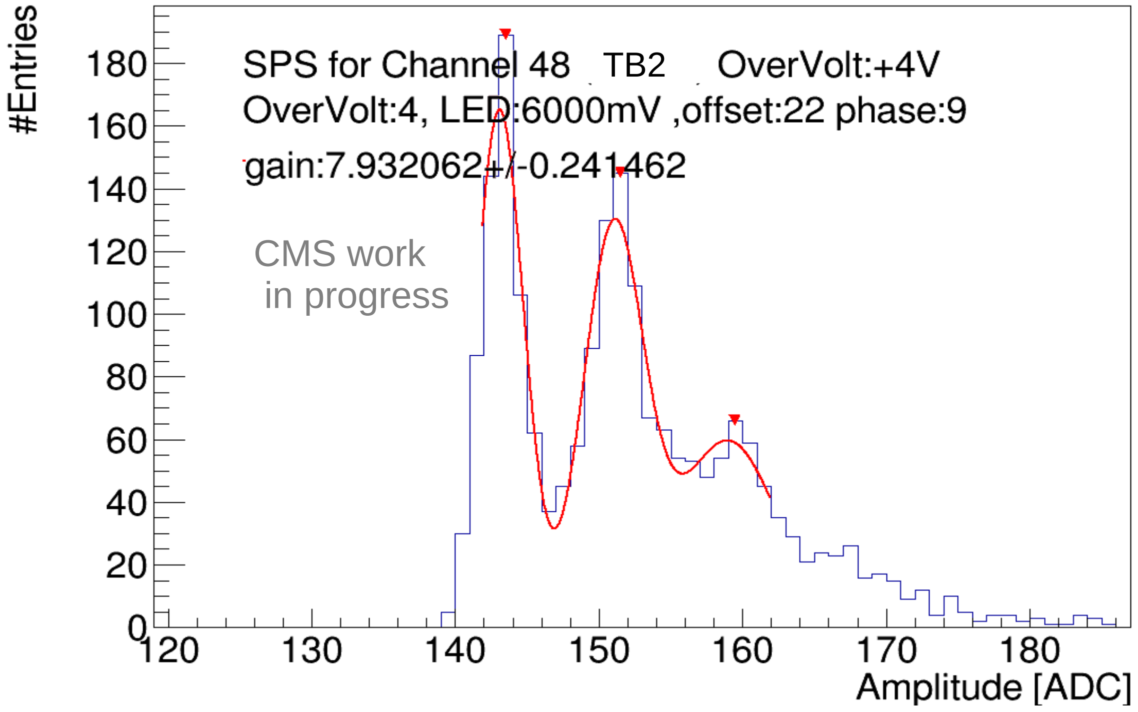




Overview of SiPM Gain Analysis

SiPM Gain measurement

- Multi-gaussian function fitting peaks at constant intervals determines the SiPM gain
- LED data is taken for multiple phases (for phases=0 to 15) and the highest gain value is chosen as the correct gain
- Linear extrapolation is used to determine the SiPM gain at OV=2V using 3V, 4V and 6V data

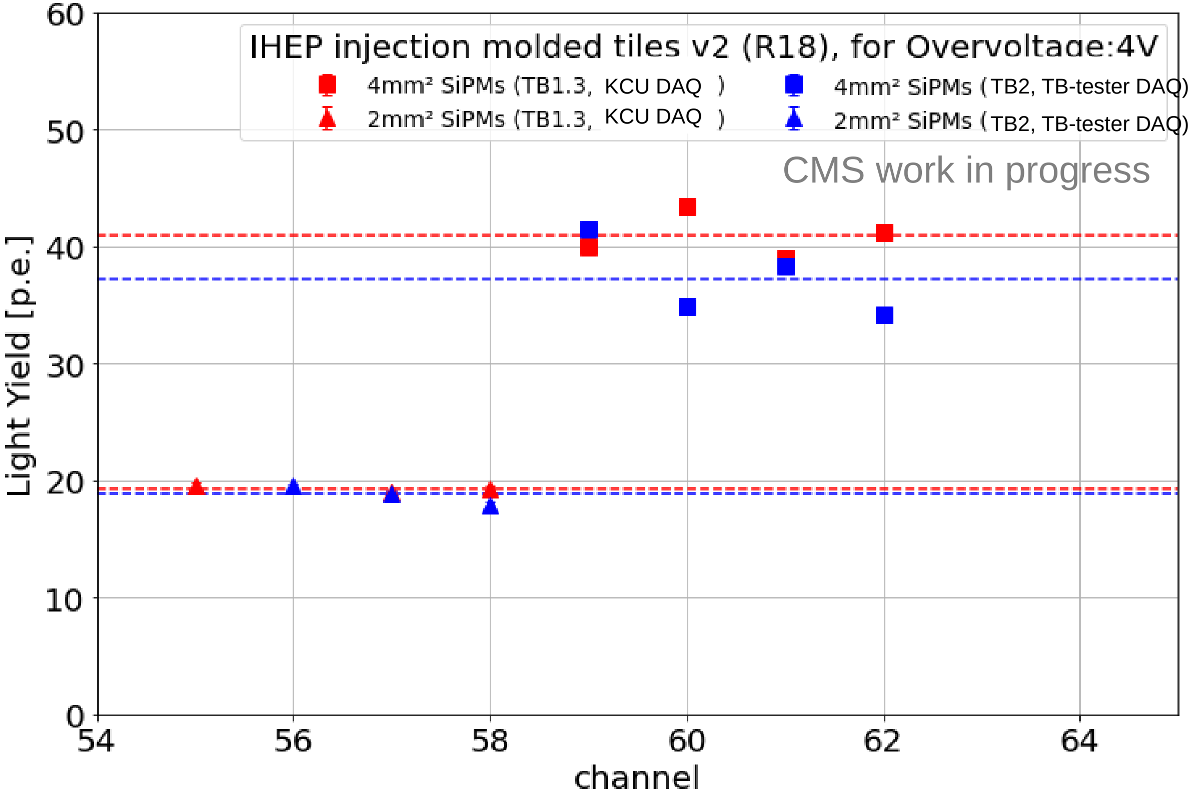


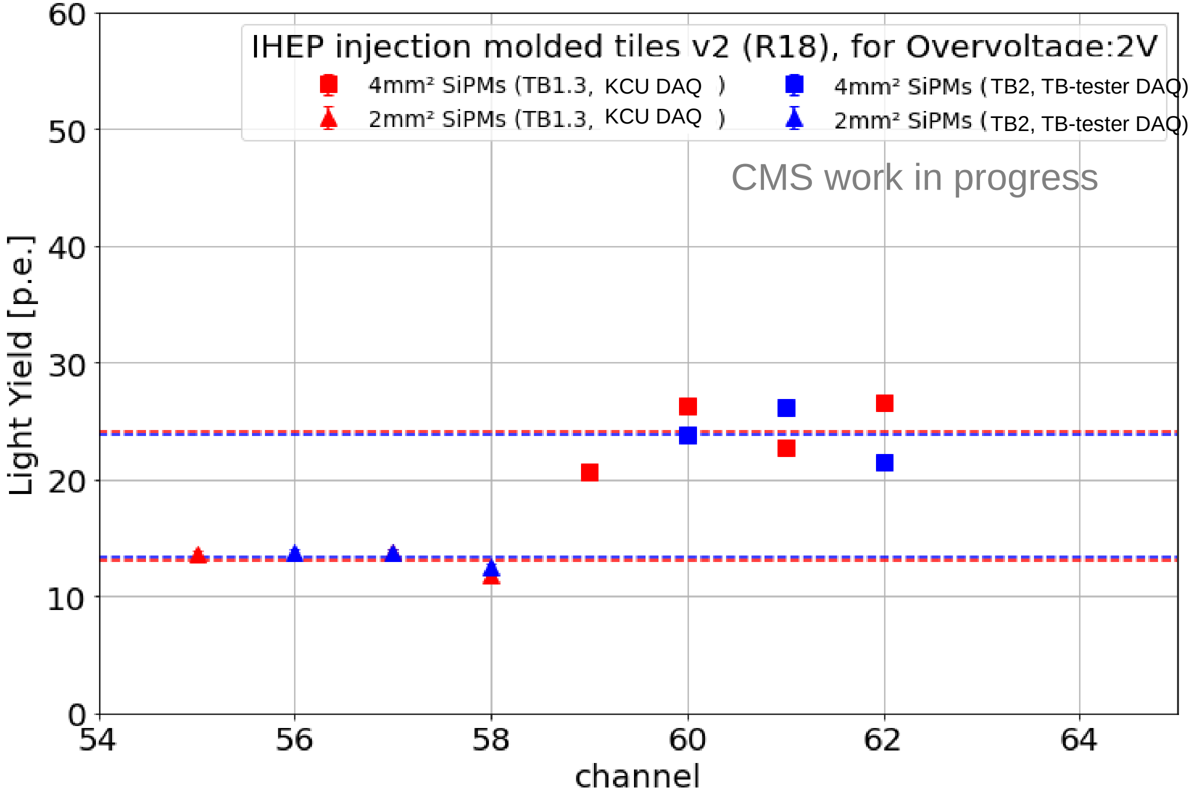
- To characterize the optical performance of the SiPM-Tile system, the signal (MPV) is normalised to the pulse height of a single fired SiPM pixel (SiPM gain) → **Light Yield [photon equivalent units (p.e.)]**

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

Comparison of Data taken with different Tileboards and DAQs

Comparison of TB2 data from February 2022

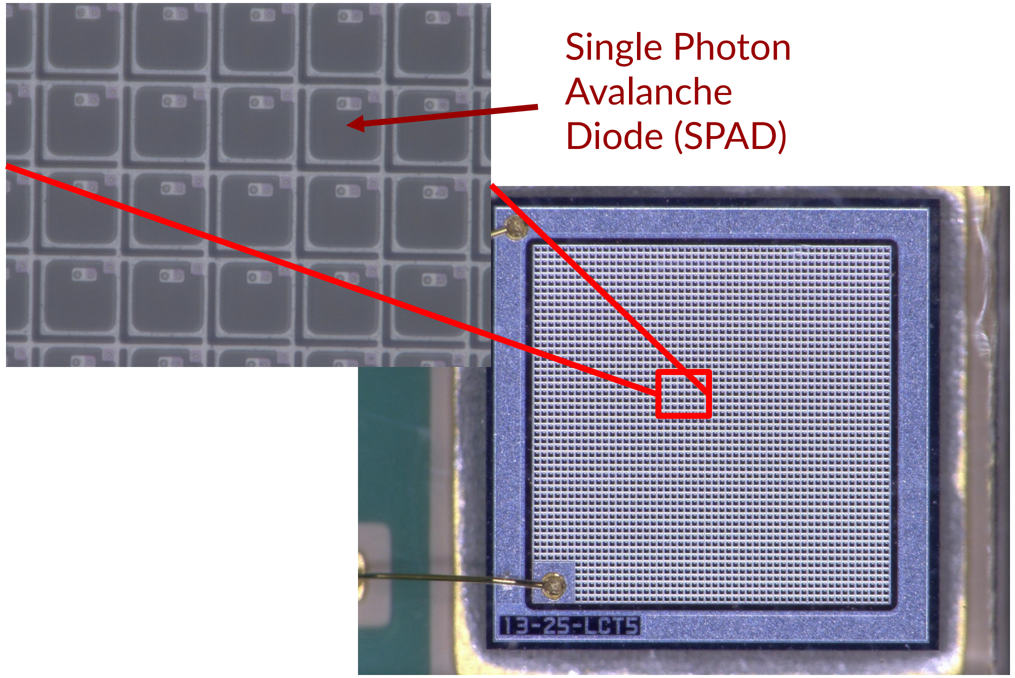


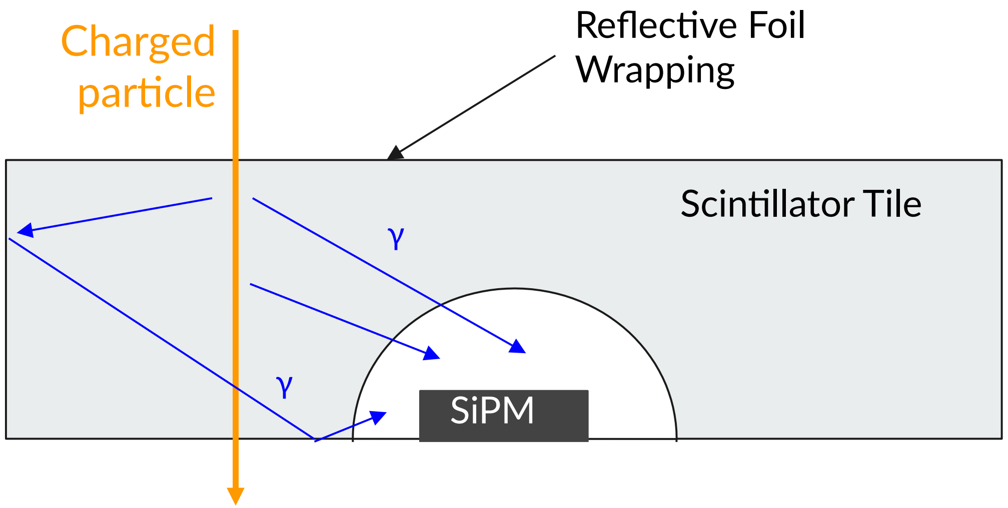


- Performance comparison with different tileboards and DAQs
  [note that both tiles and SiPMs are different despite the same channel number, so some deviation is to be expected]
  - For OV = 2V : negligible difference
  - For OV = 4V : 2-10% difference

SiPM-on-Tile technology

Working Principle





- SiPMs or MPPCs consist of 1000s of single photon avalanche diodes (SPAD)
- Each diode is sensitive to single photons

- Charged particles passing through the wrapped tiles produce scintillation photons
- These photons are reflected back onto the SiPM with the help of the reflective foil wrapping
- On-board electronics (including the HGCROC's current conveyor) amplifies signal and converts the obtained charge into digital signals
  - **ADC scale for lower gains**
  - Time over Threshold (TOT) for higher gains
  - Time of Arrival (TOA) for timing information