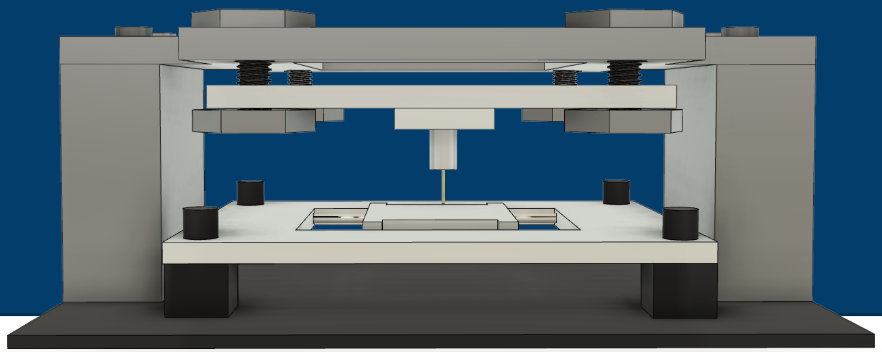
AUTOMATIZED DEDICATED MEASUREMENT SETUP FOR SiPM ARRAY CHARACTERIZATION



22 FEB 2021 I ANOOP N KOUSHIK

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JEDI

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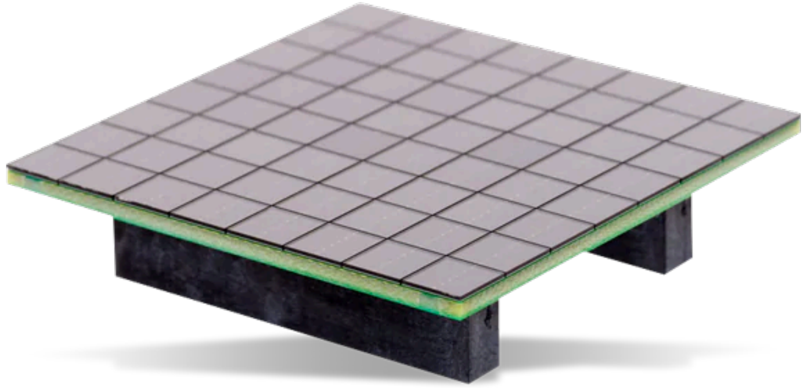
OUTLINE

INTRODUCTION TO SiPM ARRAYS

- Silicon photomultiplier (SiPM) is a solid-state photon detector with single photon counting capability.

- Each SiPM consists thousands of Single Photon Avalanche Diode (SAPD). With SAPDs set to Geiger mode and connected in parallel, resulting total current is proportional to the number of the SAPDs triggered.

- SiPM array / matrix is made of 64 (8x8) SiPM.



INTRODUCTION TO SiPM ARRAYS

- Dark current - False positive triggers of the microcell (SAPD) in absence of photon integrated over time. Usually there are 1 to a few microcell contributing as noise.

- Photon detection efficiency (PDE) - The ratio of the number of detectable photoelectrons to the number of photons incident on the SiPM. It is a function of the wavelength, applied overvolt and the fill factor.

- Responsivity - Defined as the average photocurrent produced per unit optical power:

$R = \frac{I_p}{P_{op}}$ (measured photocurrent) / (incident optical power of wavelength)

INTRODUCTION TO SiPM ARRAYS

- SiPMs are **not** very radiation hard -
  - Radiation causes damage to the Si crystal structure. Damage can also be extended to the neighbouring electronics
  - These damages increases dark current (noise) from the SiPM
  - Also results in lowering its photon detection efficiency

- 52 SiPMs are used in the JEDI polarimeter in COSY, along with the LYSO crystal, instead of PMTs.

- In this thesis, all the SiPM array modules used and the results obtained are from

SensL ArrayJ 30020 8x8

OUTLINE

MOTIVATION AND OBJECTIVE

- During the beam based alignment in 2019, an accidental irradiation of these SiPMs took place. This made characterization of the SiPMs a requisite for determining their integrity before installation for the upcoming experiments.

- The objective of this thesis was to build a standalone characterization instrument to characterize all the SiPM in the SiPM array without any human intervention.

- Obtaining a detailed report on the SiPMs in questions -> Helps to make the decision:
  - ✳Using it as is.
  - ✳Using after annealing.
  - ✳Discarding it as damaged beyond recovery.

OUTLINE

I) Introduction to SiPM arrays

II) Motivation and objective

III) Irradiation experiment at JULIC

IV) Instrumentation - Hardware and software development

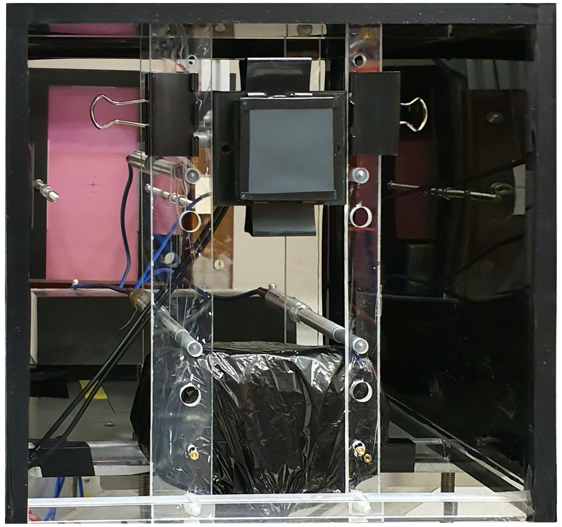
    I) Dark current characterization

    II) Responsivity characterization

V) Summary and Outlook

INVESTIGATING THE RADIATION HARDNESS OF THE SiPM ARRAYS - EXPERIMENT

- An experiment was set up at the end of cyclotron (JULIC) for the irradiating a healthy SiPM array.
- Housing for the SiPM array and its modules were designed and 3D printed.
- Radiation film was placed on the SiPM array to observe the radiation pattern and uniformity.
- Dark current was measured during irradiation and also when radiation was switched off. Data recorded and analysed on the Raspberry Pi.
- Live feed of the dark current was being plotted on the web interface to observe the changes instantly.



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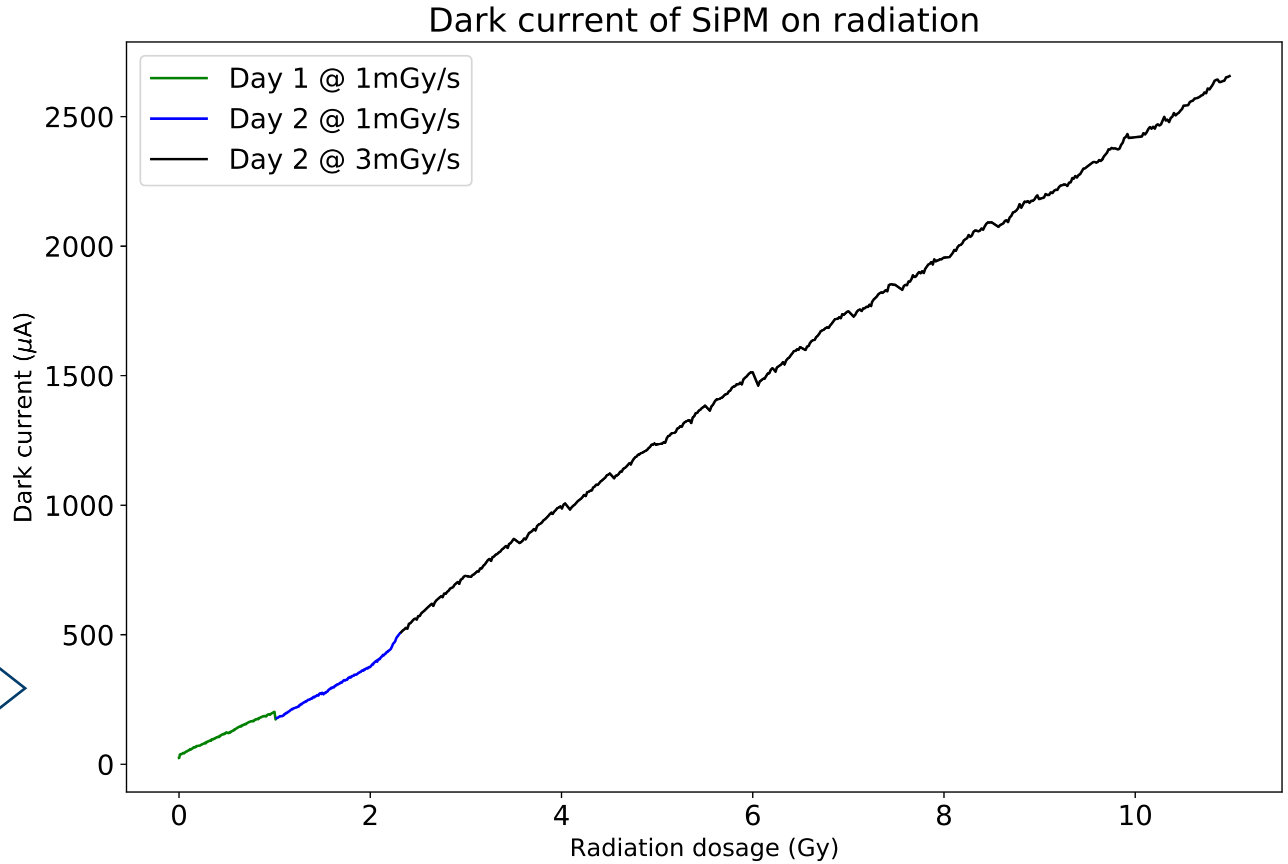
INVESTIGATING THE RADIATION HARDNESS OF THE SiPM ARRAYS - RESULTS

- SiPM array was irradiated up to 11 Gy in total in steps.

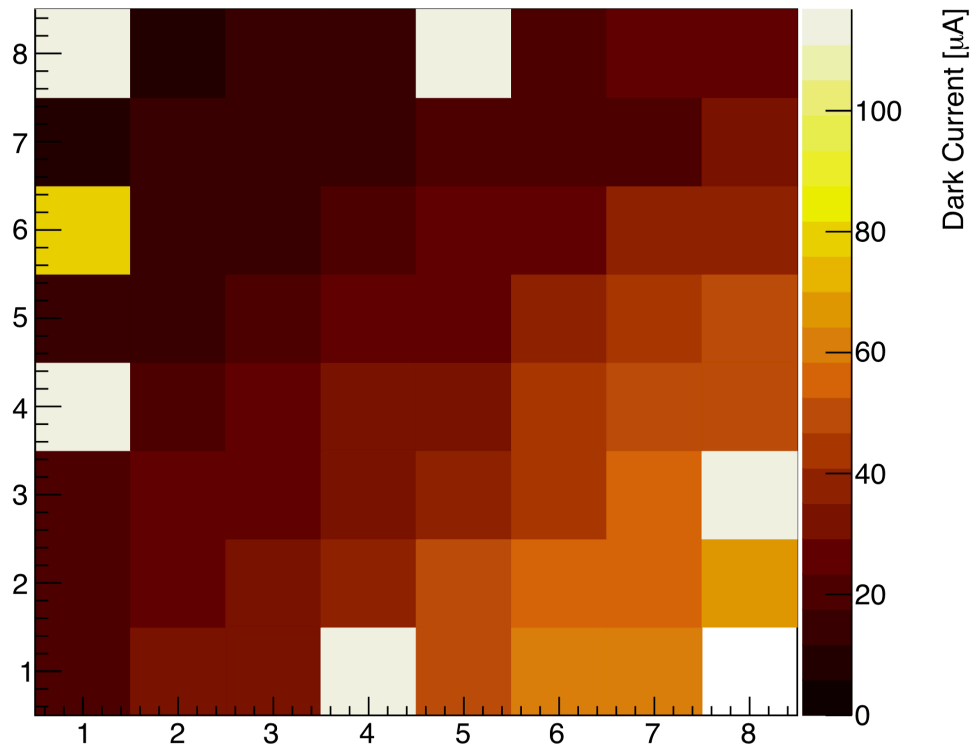
- Radiation damage in the experiment was similar to the damage caused during beam based alignment of the SiPM arrays in the second ring.

- Dark current of the SiPM array when the radiation was turned off, is shown

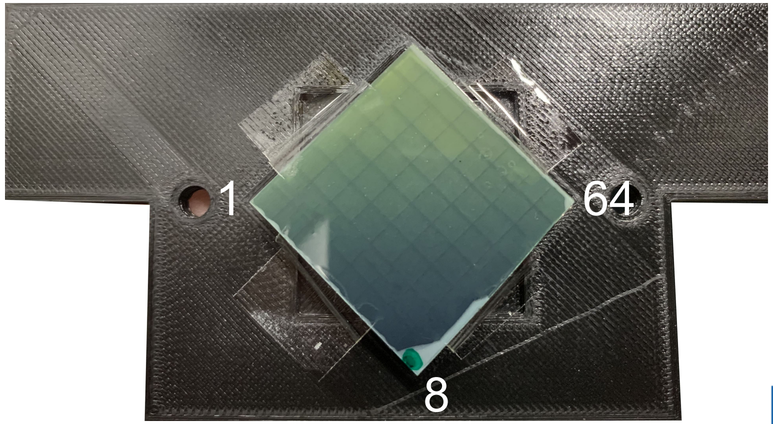


INVESTIGATING THE RADIATION HARDNESS OF THE SiPM ARRAYS - RESULTS

- Dark current map of the SiPM array at 26V from the irradiation experiment is shown

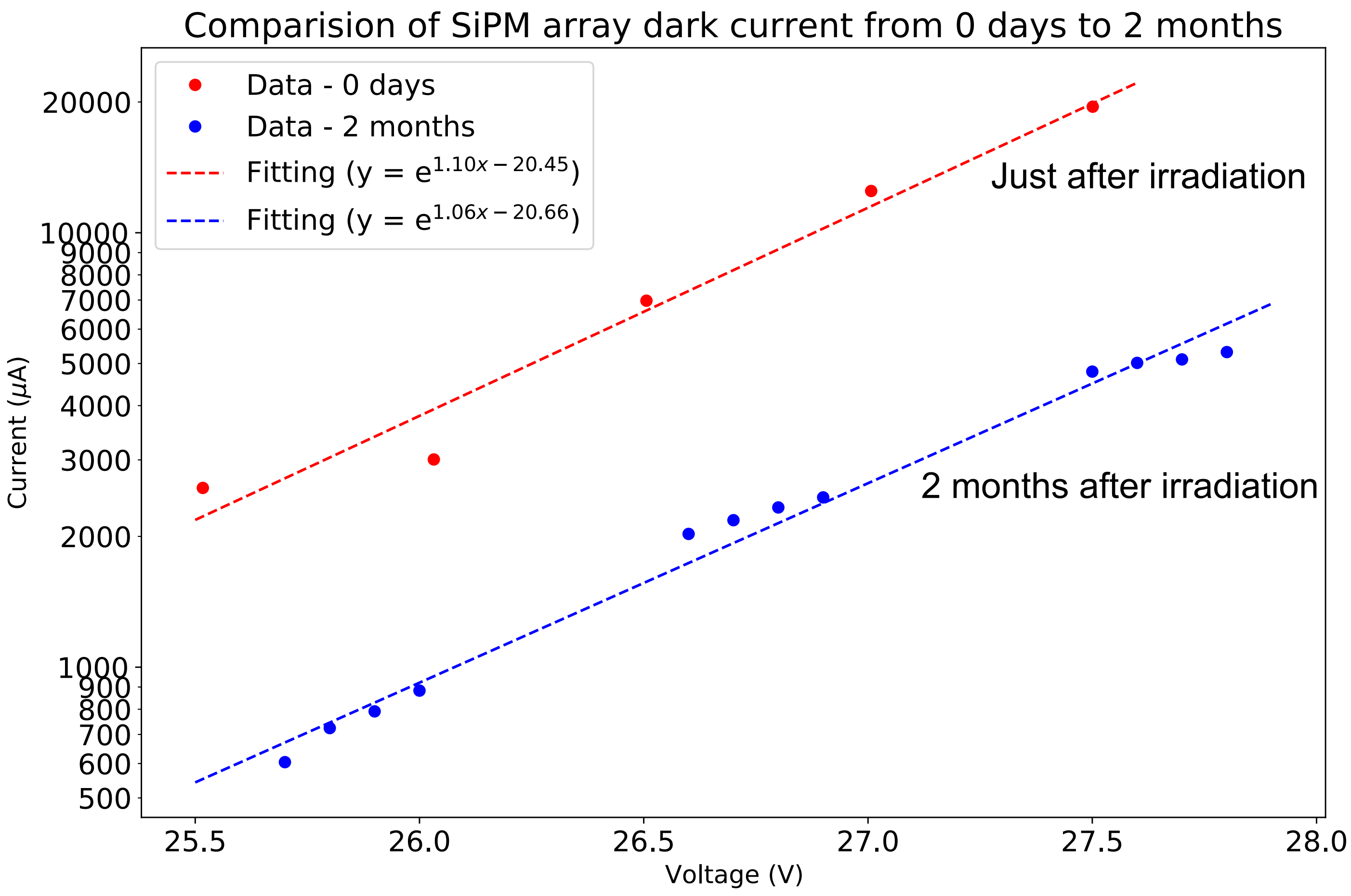


- SiPM number 8 (lower right corner) was pointing down towards the centre of the radiation beam.
- A clear pattern of the increase in the dark current is seen where the radiating beam was incident on the SiPM array.



INVESTIGATING THE RADIATION HARDNESS OF THE SiPM ARRAYS - RESULTS

- Data of dark current which was measured after the irradiation experiment.
- Change in dark current over the period of 2 months of room temperature annealing.
- Data was recorded every 12 hours for different voltages for a period of 7 days.
- Reduction in dark current up to 4 times in 2 months.



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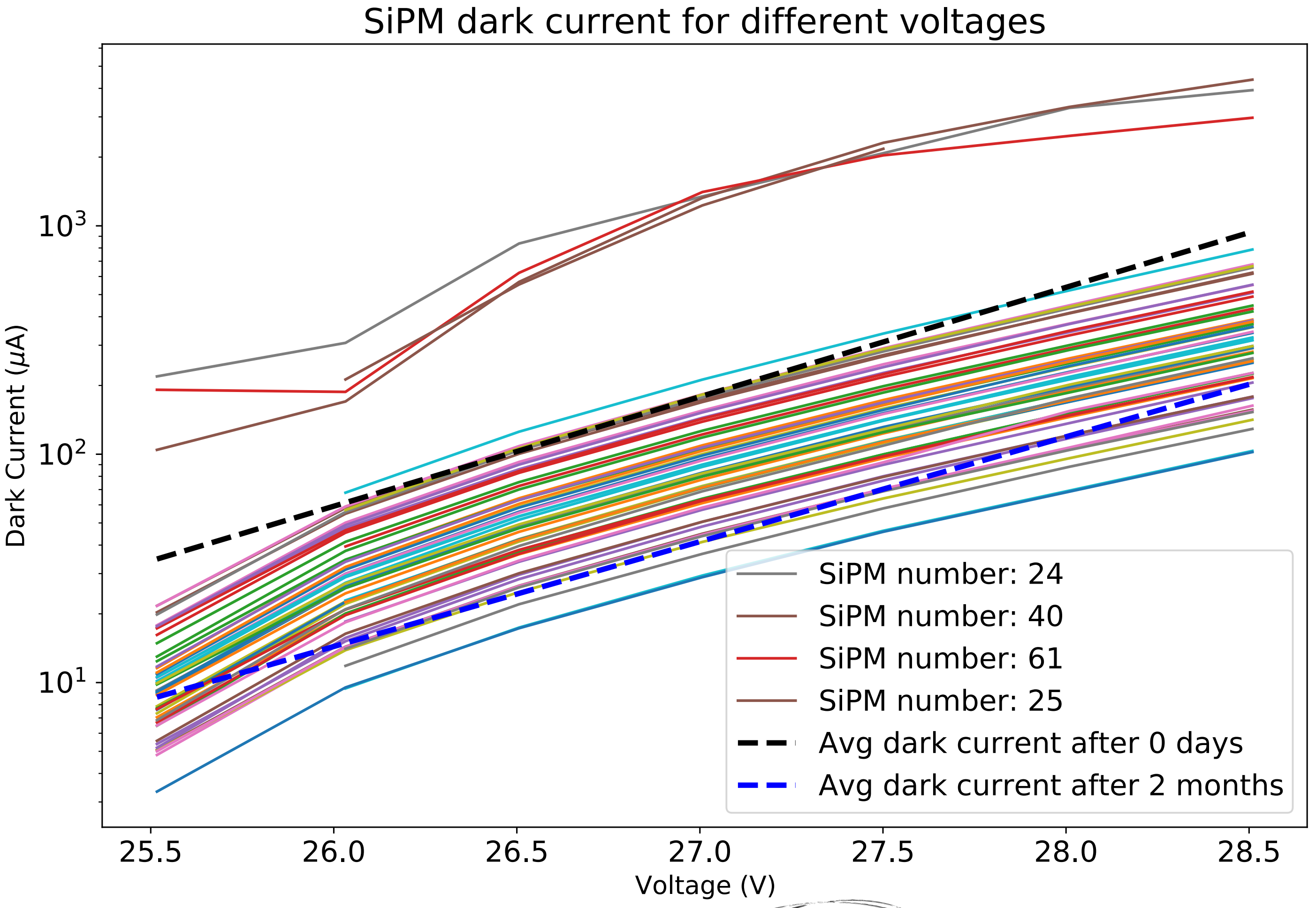
INVESTIGATING THE RADIATION HARDNESS OF THE SiPM ARRAYS - RESULTS

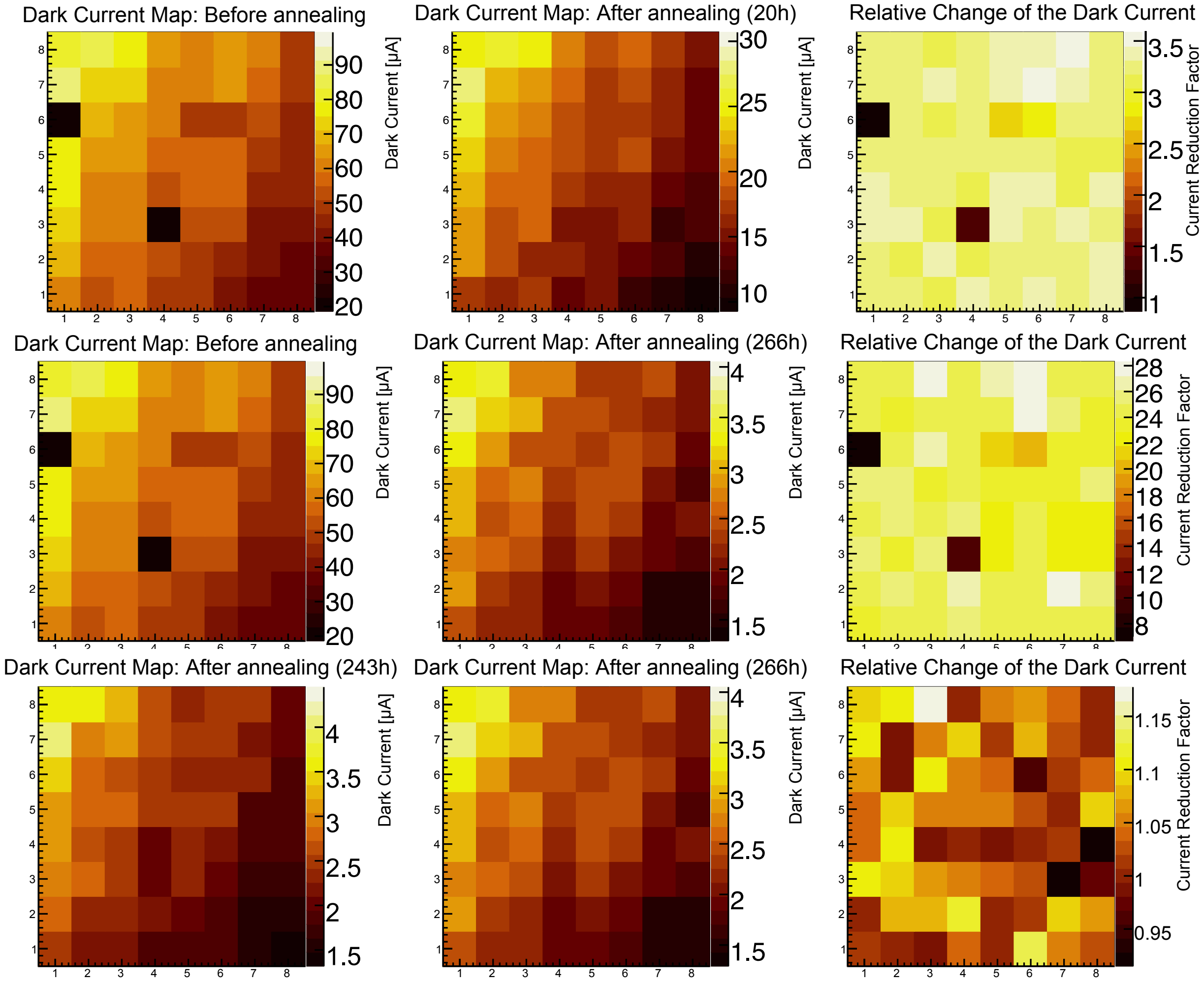
- Line (black) shows average of the dark current after the irradiation experiment.
- Line shows average dark current measured after 2 months.
- Few SiPMs were severely damaged.
- Few SiPMs remained healthy (due to less incident radiation).
- Exponential dependence of dark current on voltage can be observed.



INVESTIGATING THE RADIATION HARDNESS OF THE SiPM ARRAYS - RESULTS

Accidental damage - Annealing in oven @ 120°C

- Damaged SiPM array were subjected to high temperature annealing.
- Comparison reports of SiPM which was subjected to annealing in oven is shown on the right.
- Change in dark current can be visualised.
- SiPM damaged by radiation produces much higher dark current than the rest average. Dark current reduces after annealing and saturates.
- Examples:
  - ➡0 - 20 hours annealing
  - ➡0 - 266 hours annealing
  - ➡243 - 266 hours annealing

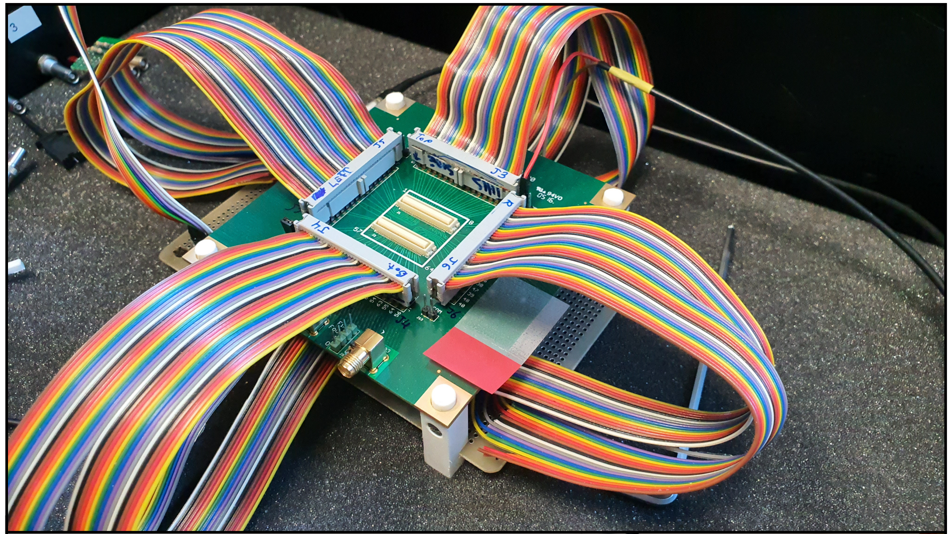


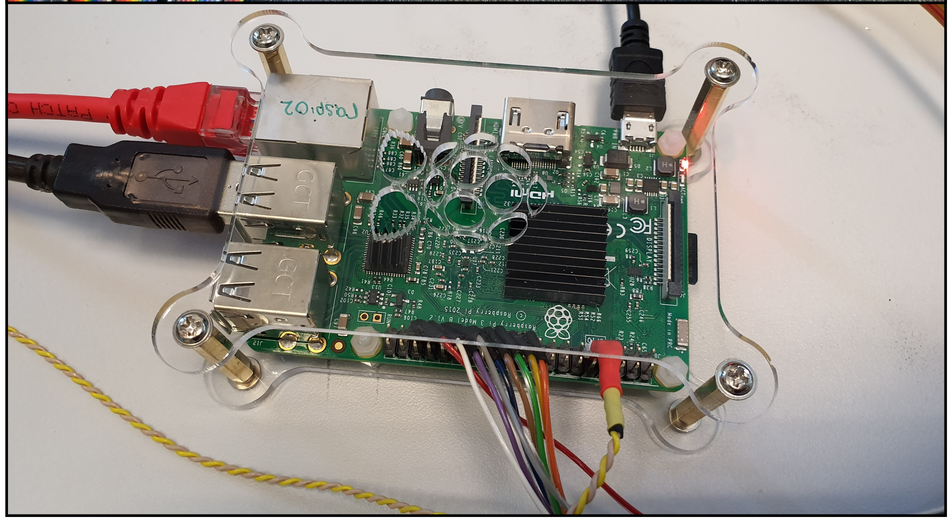
OUTLINE

AUTOMISED SiPM CHARACTERISATION TOOL

DARK CURRENT

- SiPM matrix has 64 SiPMs.
- 5 multiplexers (mux) used to channel each SiPM from SensL Evaluation Board (BOB3).
- Mux channels was controlled and data recorded by the Raspberry Pi.

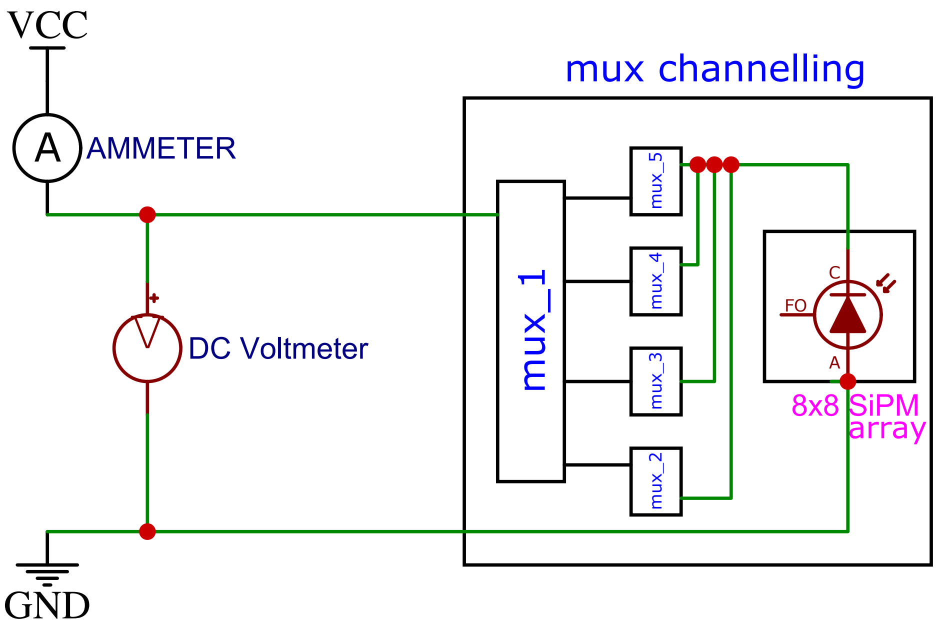


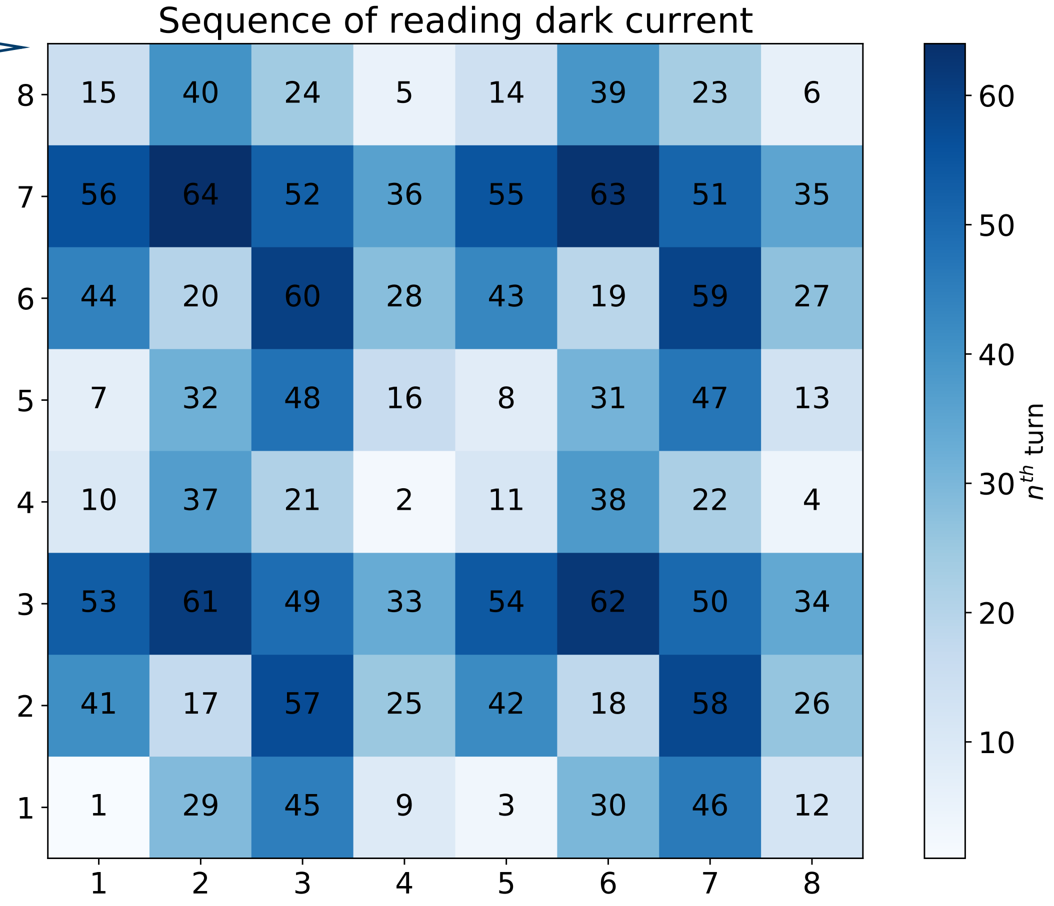


AUTOMISED SiPM CHARACTERISATION TOOL

DARK CURRENT

- An algorithm was devised to avoid heating issue - reads SiPM which are always the farthest from the previous SiPM
- Simple 5 mux channeling schematics is shown below

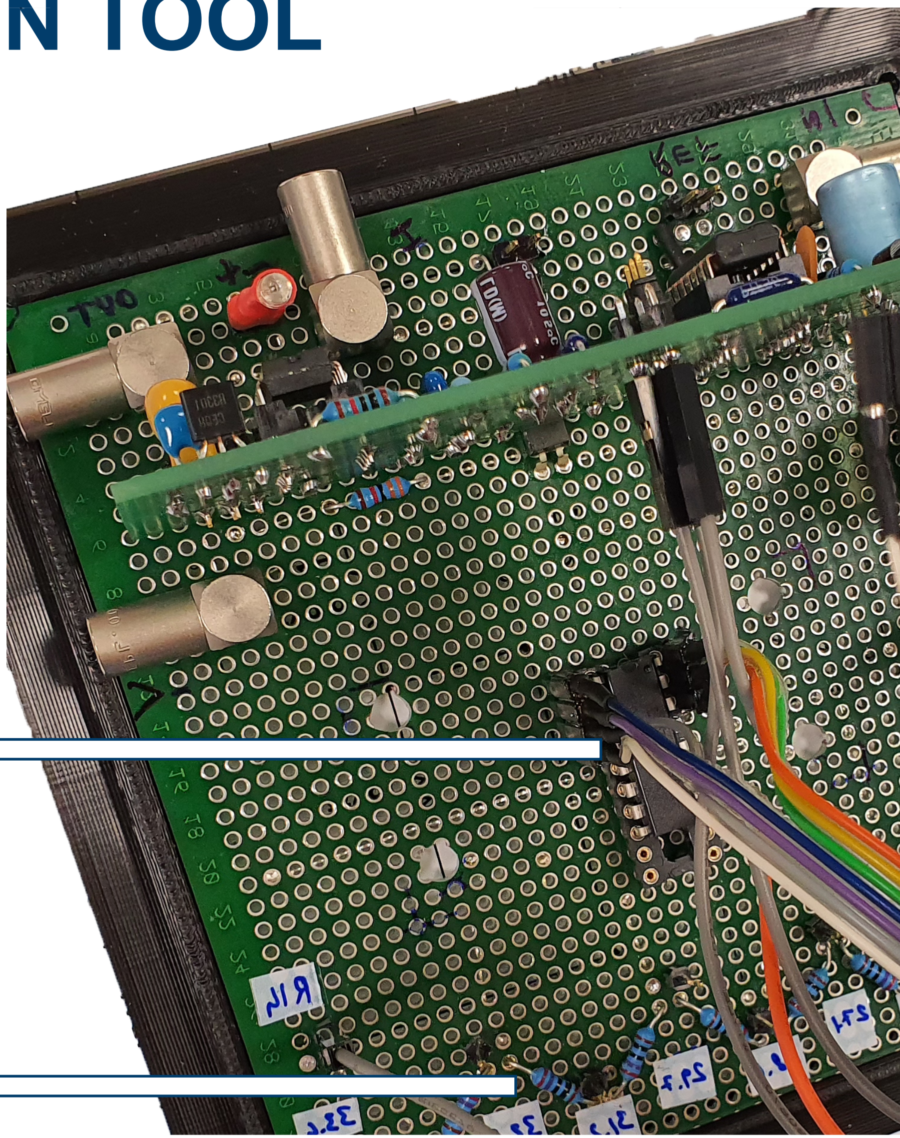




AUTOMISED SiPM CHARACTERISATION TOOL

DARK CURRENT

- On board potentiometer in power supply circuit was replaced by a series of resistors connected to a multiplexer at each node.
- In simpler terms, a digital potentiometer.
- Scanning dark current through pre-determined voltages is possible.



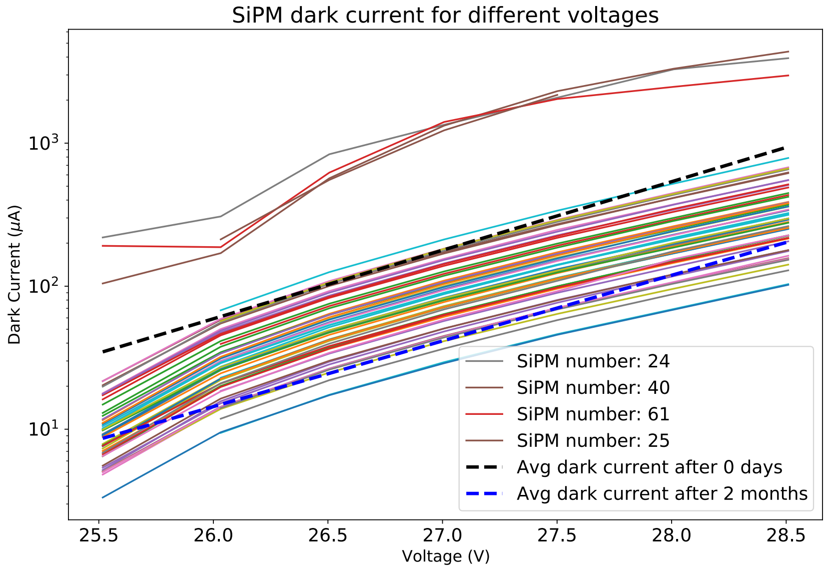
Multiplexer

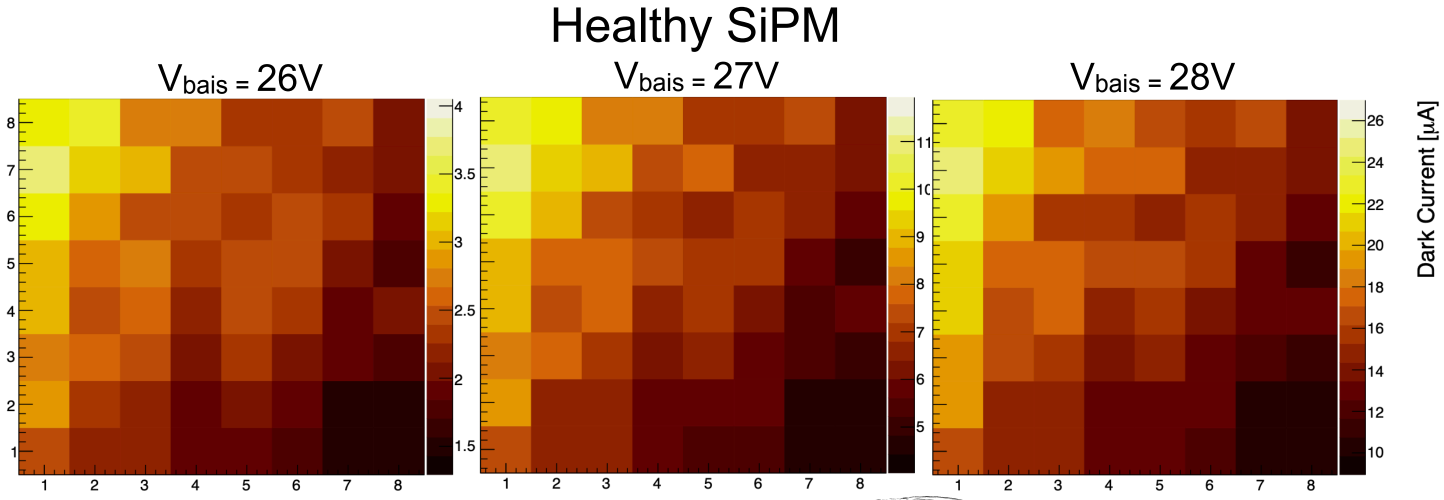
Resistors

AUTOMISED SiPM CHARACTERISATION TOOL

DARK CURRENT - RESULTS

- This tool was used in the analysis of the project "Investigating the radiation hardness of the SiPM arrays".
- Dark current for different voltages for each SiPM in the array are recorded.
- Data is then analysed and PDF are generated instantly.





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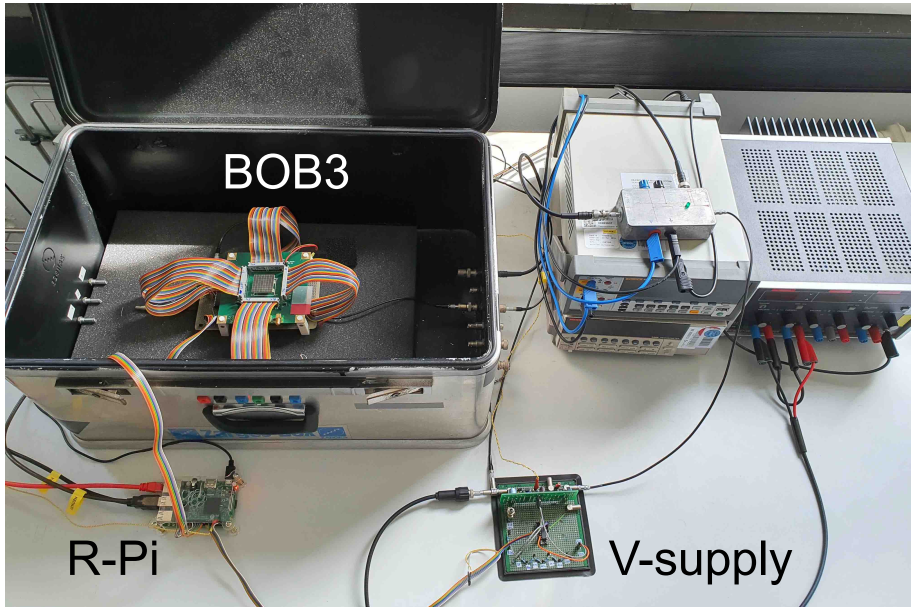
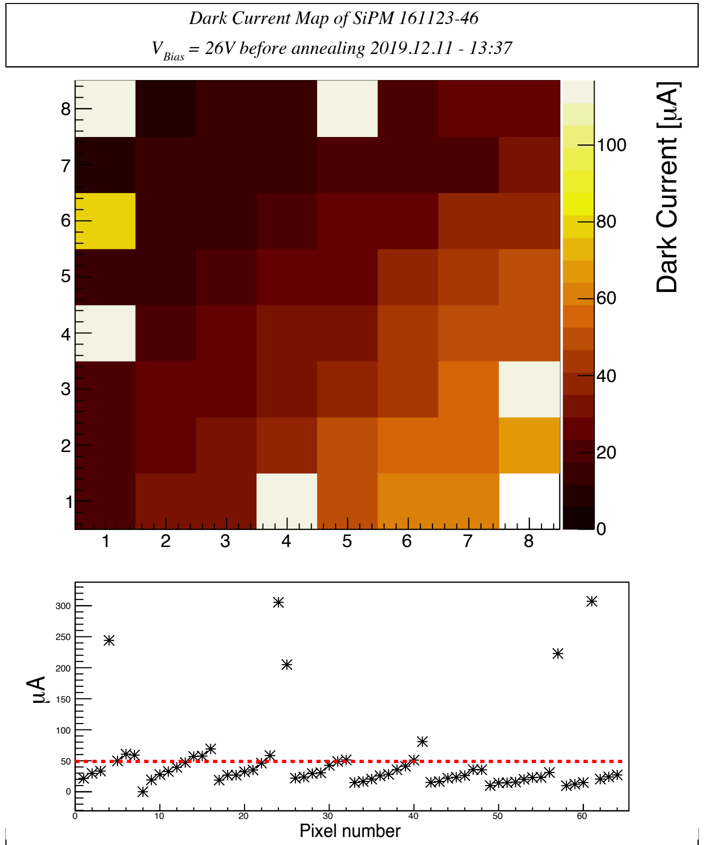
AUTOMISED SiPM CHARACTERISATION TOOL

DARK CURRENT REPORT

- Sample report of an irradiated SiPM and annealed SiPM (266 hours).
- Final set-up is shown below.





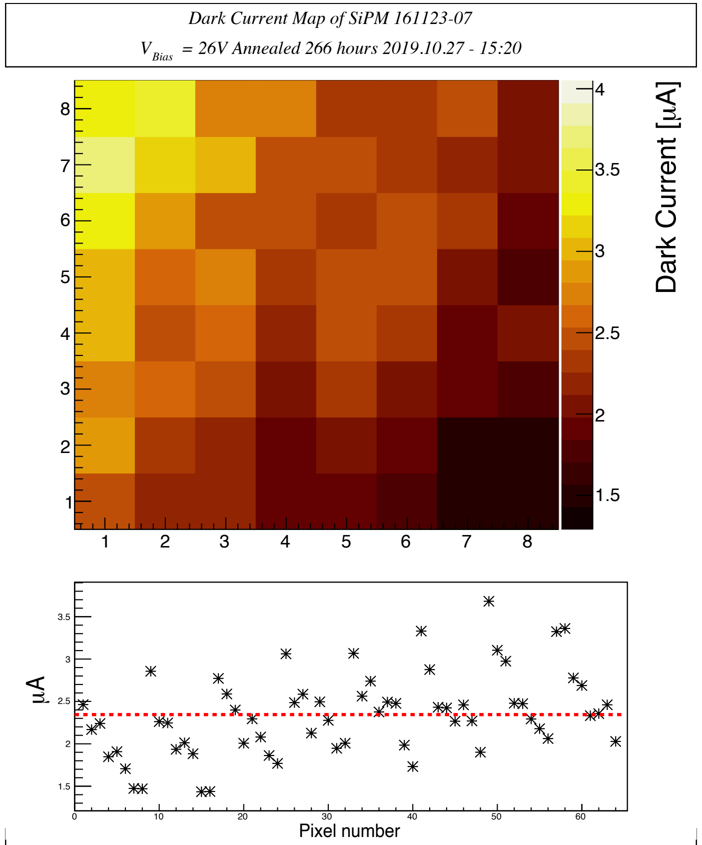
Total current = 3129.587 µA

Average = 48.900 µA

RMS = 63.621 µA

Maximum Current = 307.104 µA @pixel 60

Minimum Current = -0.006 µA @pixel 7



Total current = 150.065 µA

Average = 2.345 µA

RMS = 0.482 µA

Maximum Current = 3.682 µA @pixel 48

Minimum Current = 1.434 µA @pixel 14

AUTOMISED SiPM CHARACTERISATION TOOL

RESPONSIVITY

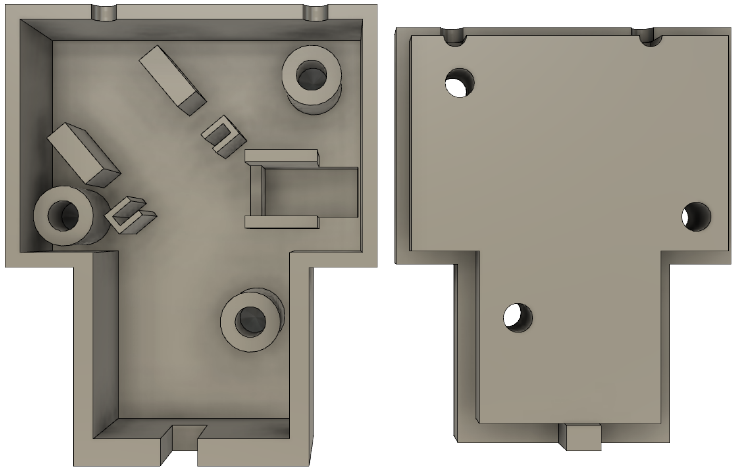
- Need to illuminate each SiPM in the array with the exact same conditions.
- Instrument basic components:
  - ➡ 2 x stepper motor with trays (1 axis of motion, each) controlled with motor driver.
  - ➡ Illumination module with a reference SiPM inside to record the light from the LED.
  - ➡ RedPitaya to control the motors and Arbitrary Function Generator (AFG), and record data from oscilloscope.
- 3D design and mechanical simulation of the structure with modules in place was performed and 3D printed

AUTOMISED SiPM CHARACTERISATION TOOL

RESPONSIVITY

Illumination Module - Key goals

- Area of illumination is as close to the area as one SiPM in the SiPM array.
- The light from the LED is measured each time when a SiPM is illuminated.
- Ability to add or remove filter for the reference SiPM / reflection of the beam.
- Detachable / replaceable. Instrument has 2x2cm socket for the illumination module.



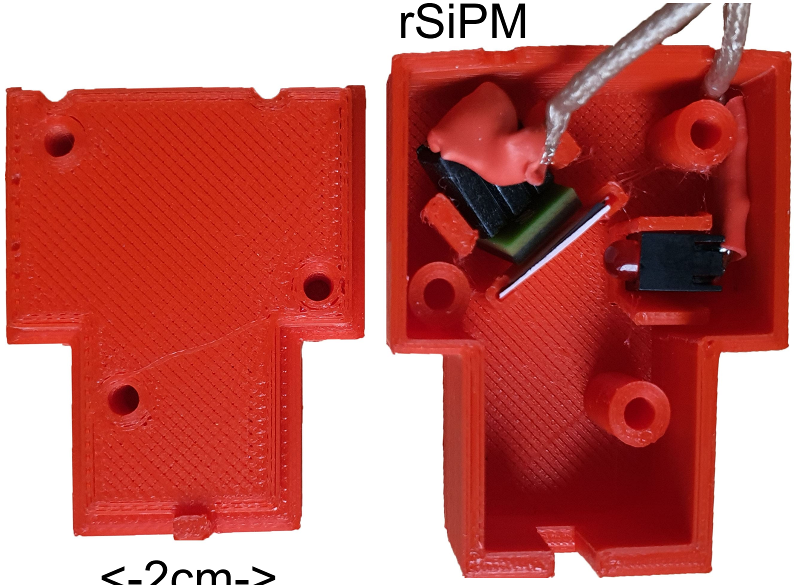


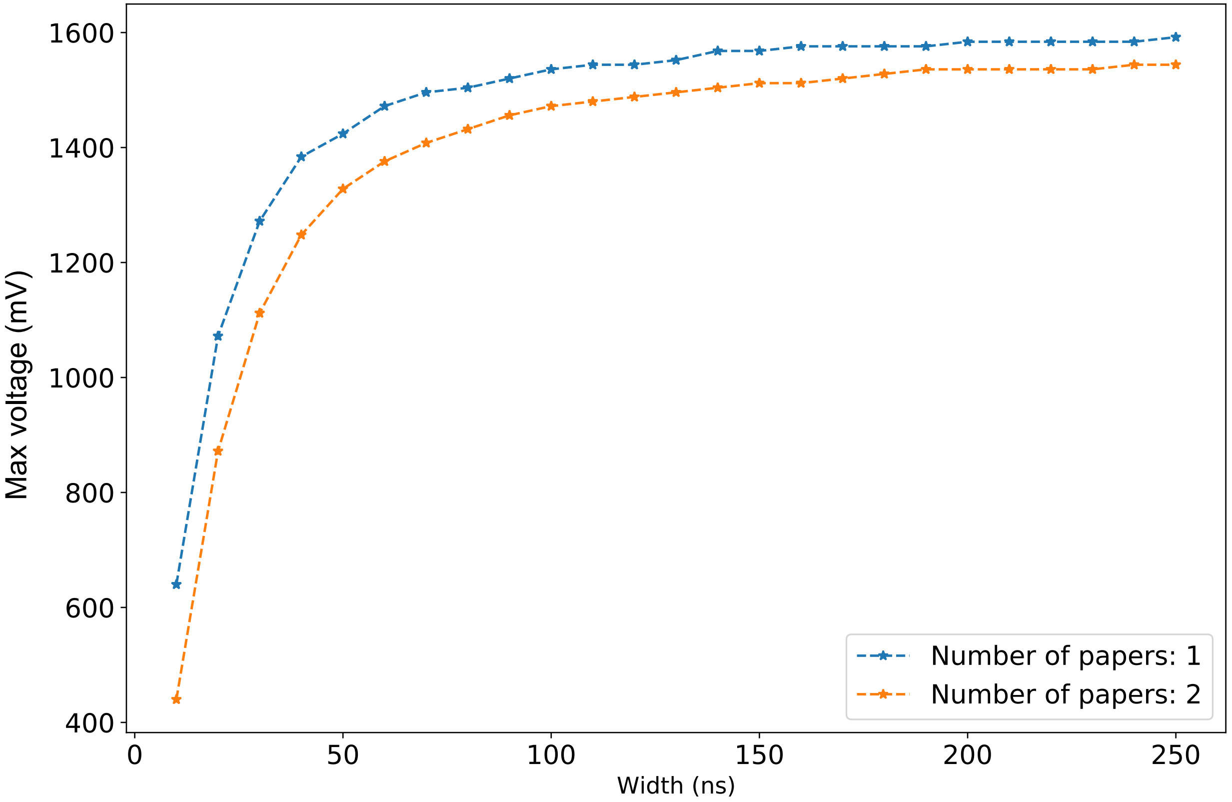
Image:

Top - CAD image of the illumination module.

Bottom - 3D printed with rSiPM, filters and a red LED

OPTIMISING PARAMETERS OF THE INSTRUMENT

- **Saturation of the reference SiPM**
  - Decay time of LYSO is 40 ns. So we can operate the LED within 40 ns to stay within the real limits.
  - Saturation is not reached. More microcells are triggered before all the others are triggered



- Light spread of the LED

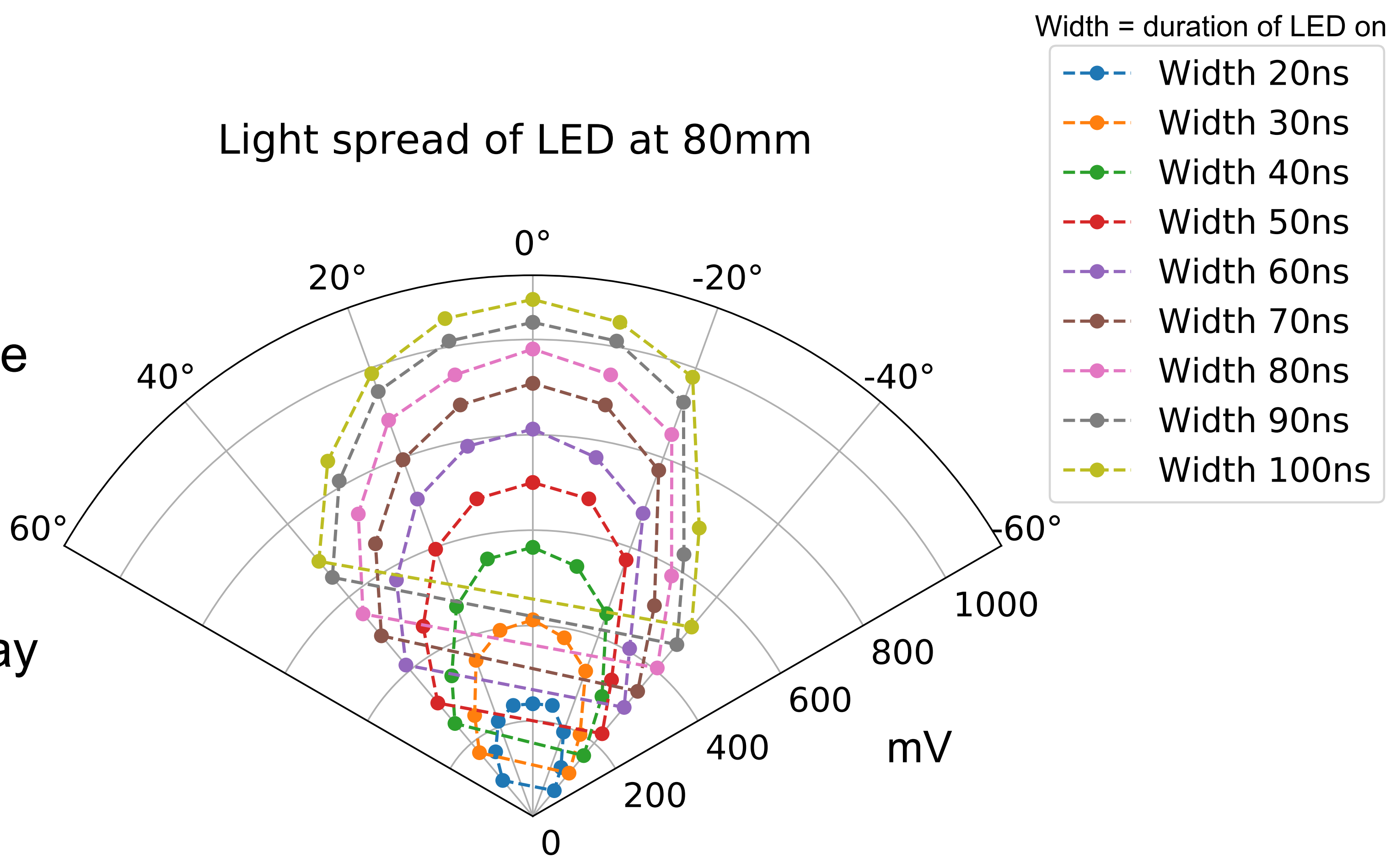
- Angular absorbance of the SiPM array

OPTIMISING PARAMETERS OF THE INSTRUMENT

- Saturation of the reference SiPM

- **Light spread of the LED**
  - Light spread up to ±10° is nearly the same regardless of the duration of the on state or distance.

- Angular absorbance of the SiPM array



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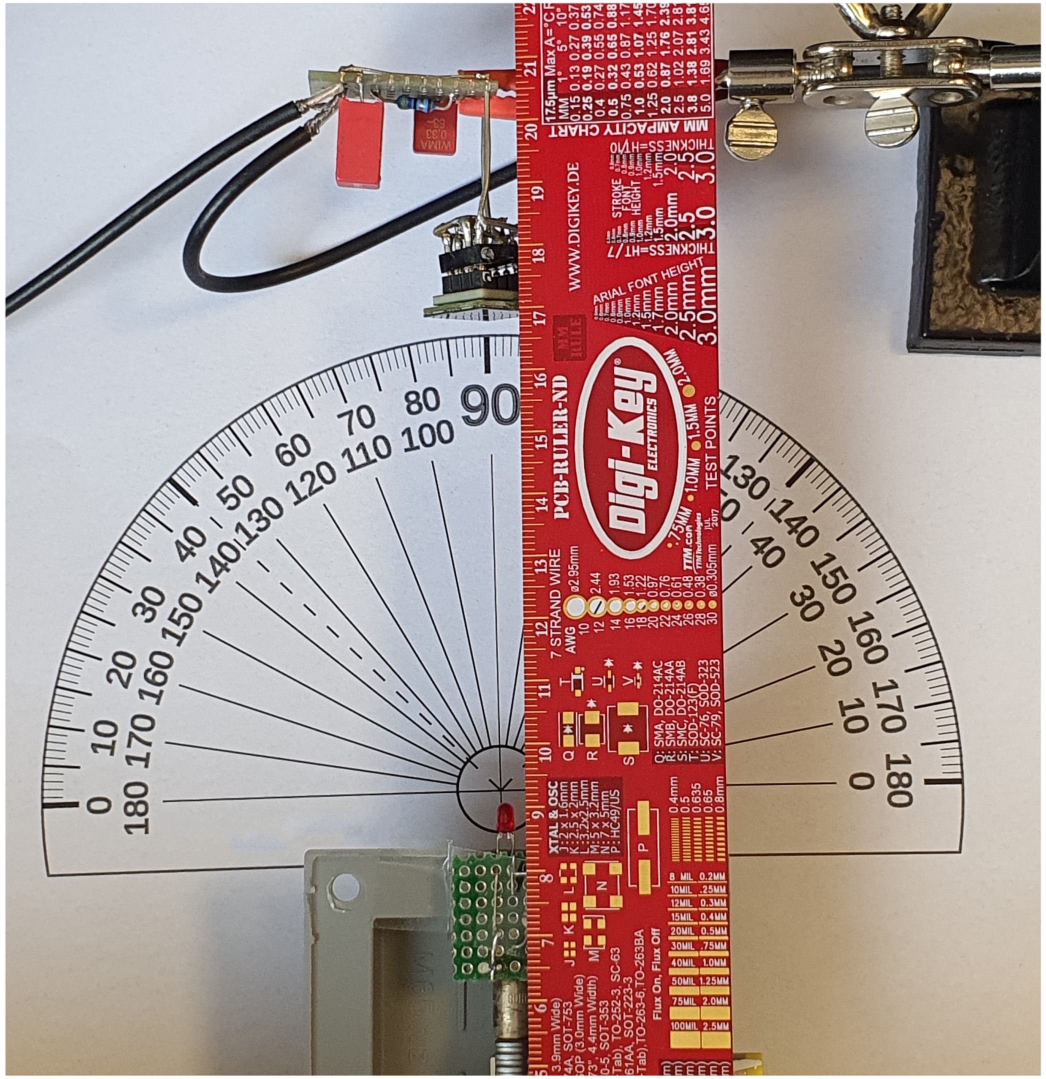
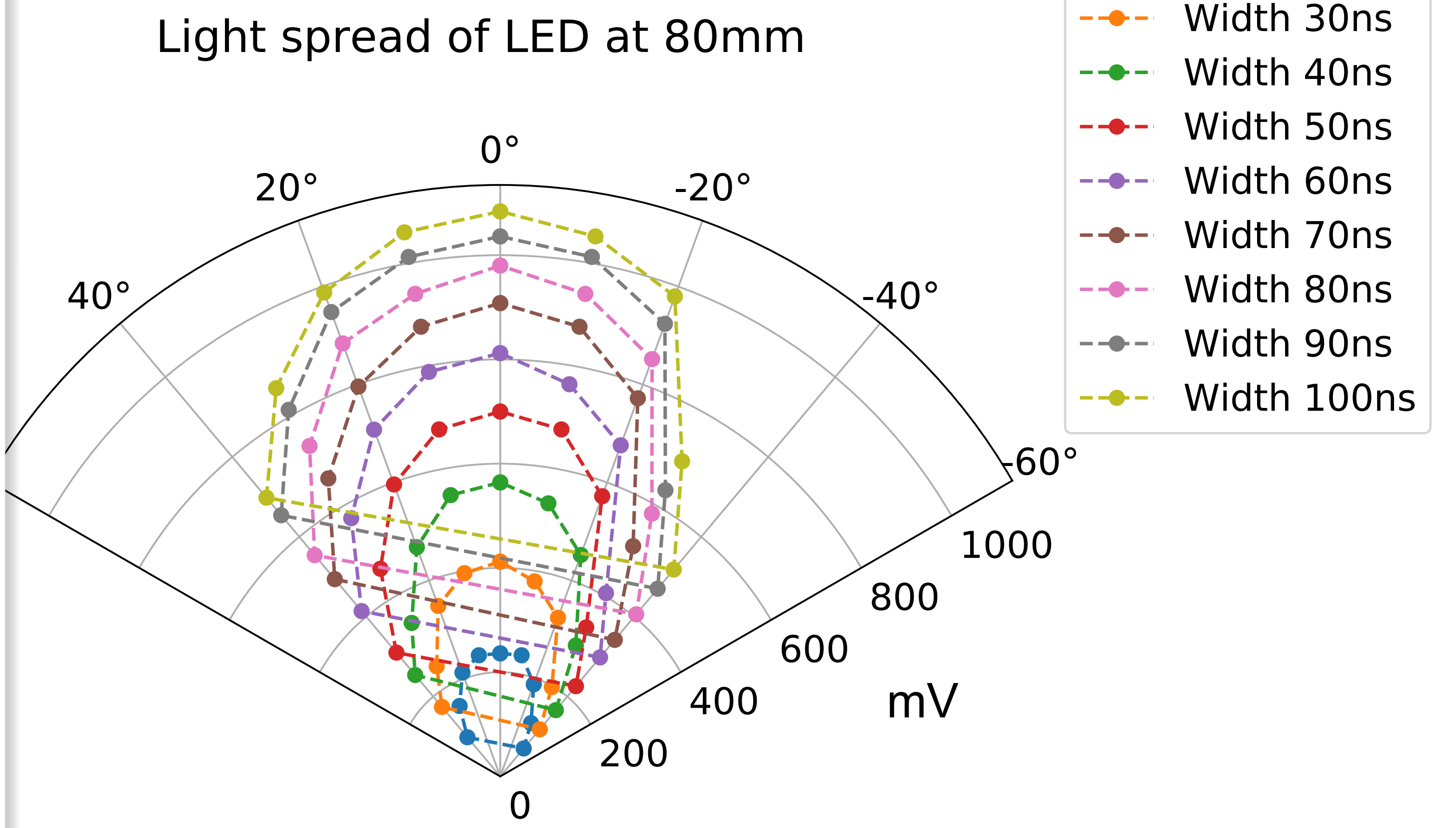
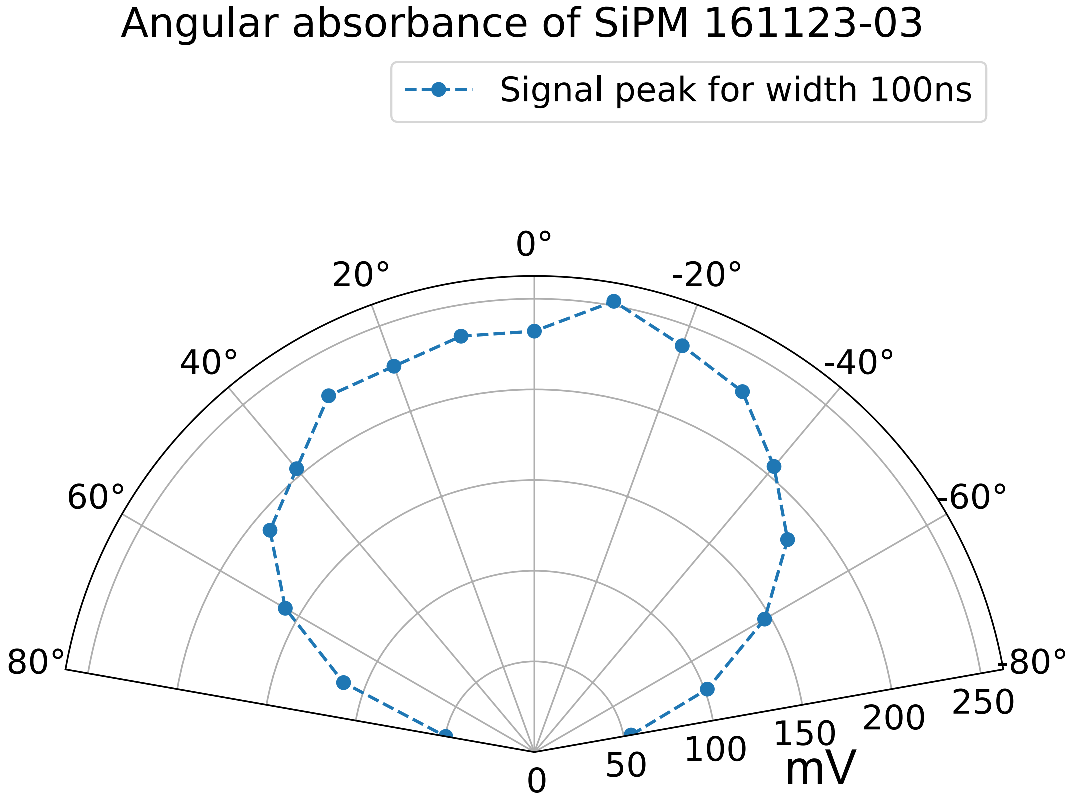
OPTIMISING PARAMETERS OF THE INSTRUMENT





OPTIMISING PARAMETERS OF THE INSTRUMENT

- Saturation of the reference SiPM
- Light spread of the LED
- **Angular absorbance of the SiPM array**
  - Angular absorbance for the SiPM array is nearly the same for a wide angle.



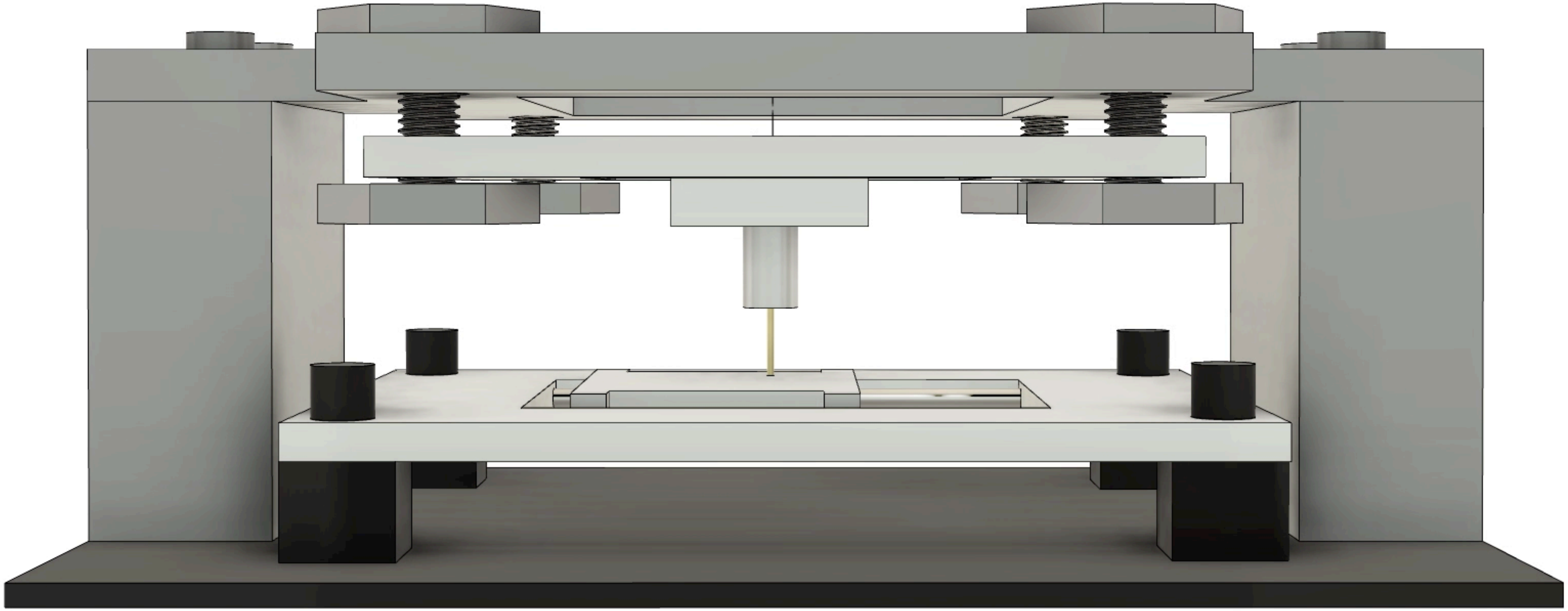
(Kink at -10° is due to setup anomaly)

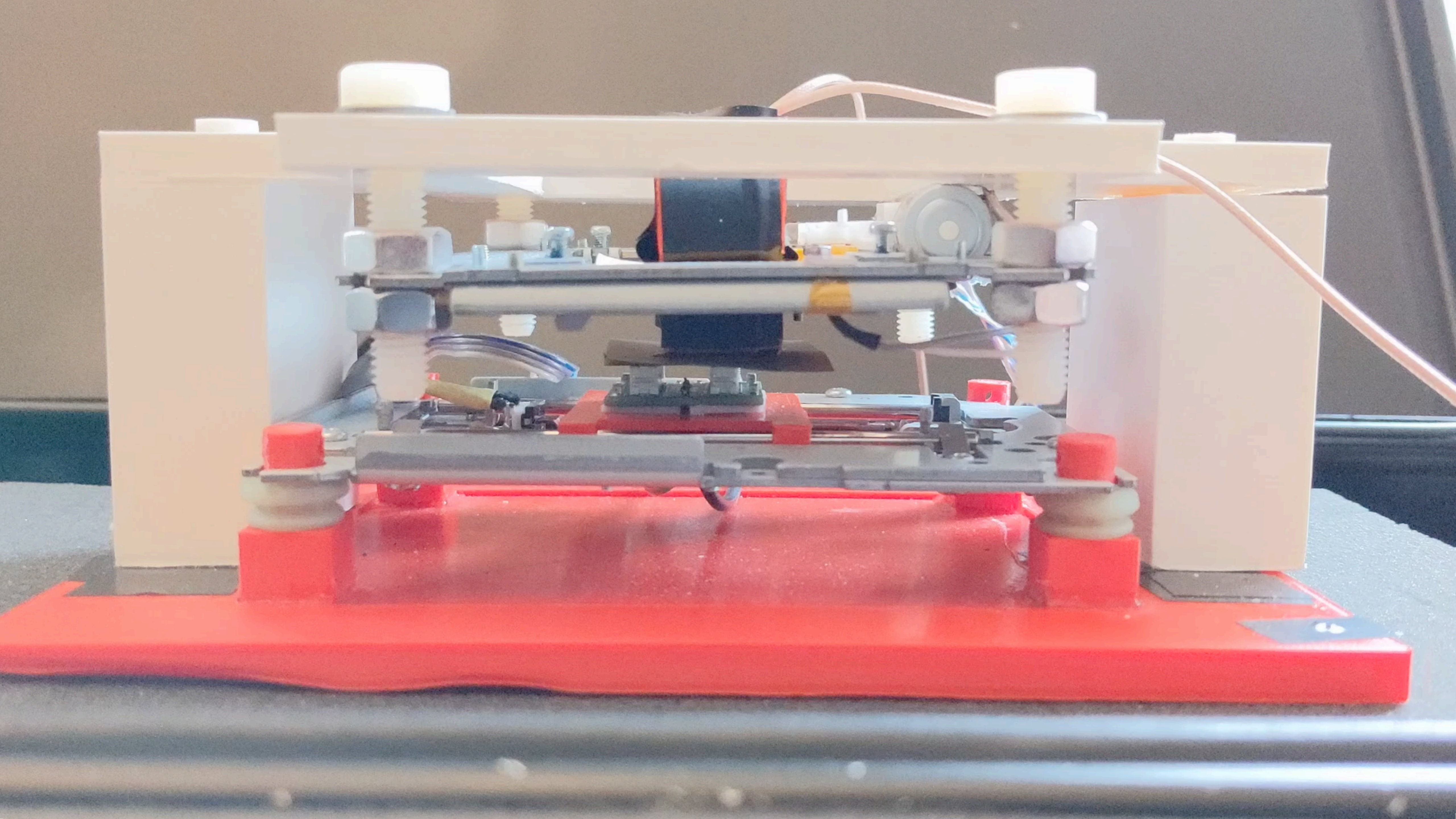
OPTIMISING PARAMETERS OF THE INSTRUMENT

- The angle of the LED can be change by large angles to reduce the overall light intensity.

- Small change in the xy-plane or small angle in the incidence of light does not have drastic change in the results.

- Have normal incidence of the light is ideal. In reality, there is small angle difference which causes reflection and scattering probability illuminating other SiPM in the array.



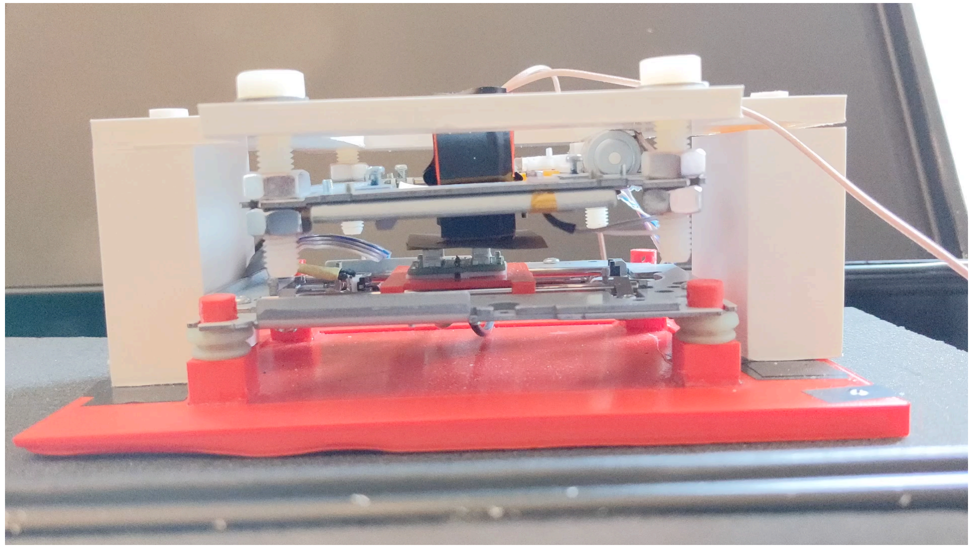


AUTOMISED SiPM CHARACTERISATION TOOL

<u>RESPONSIVITY</u>

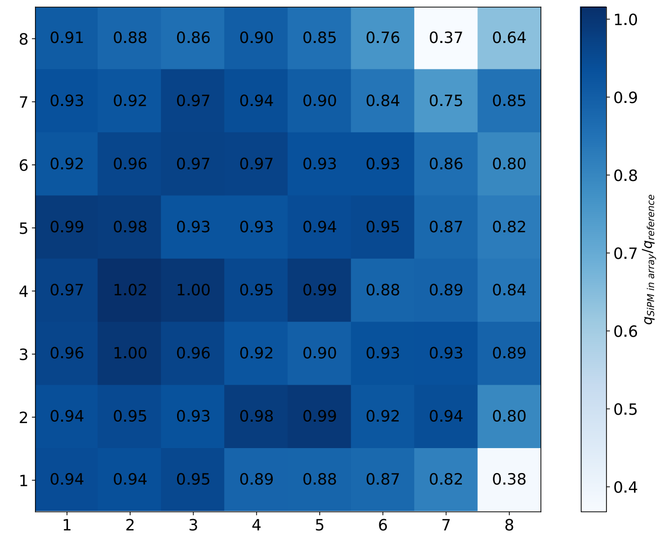
REPORT

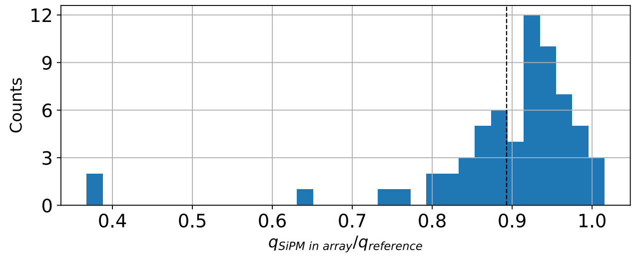
- Sample report of a healthy SiPM array with 2 missing SiPMs.
- SiPM 8 and 63 are missing
- The small readings are due to the reflections and scattering and hence this is taken as the lower bound.



Relative responsivity map for SiPM 161123-24

Bias voltage for SiPM array = 30V, 2020-12-10 17:35:00





Highest count = 12 @ 0.92 relative charge

Average = 0.89

RMS = 0.90

Highest value = 1.02 @ SiPM [26]

Lowest value = 0.37 @ SiPM [63]

AUTOMISED SiPM CHARACTERISATION TOOL
DARK CURRENT + RESPONSIVITY

- The extent of damage to the SiPM array is now known by analysing the dark current and relativity responsivity.
- The health status of the SiPM and its limits with a detailed printable report in PDF is obtained.
- From the report one can decide if SiPM array is healthy enough to be used in an experiment; based on requirements.

OUTLINE

I) Introduction to SiPM arrays

II) Motivation and objective

III) Irradiation experiment at JULIC

IV) Instrumentation - Hardware and software development

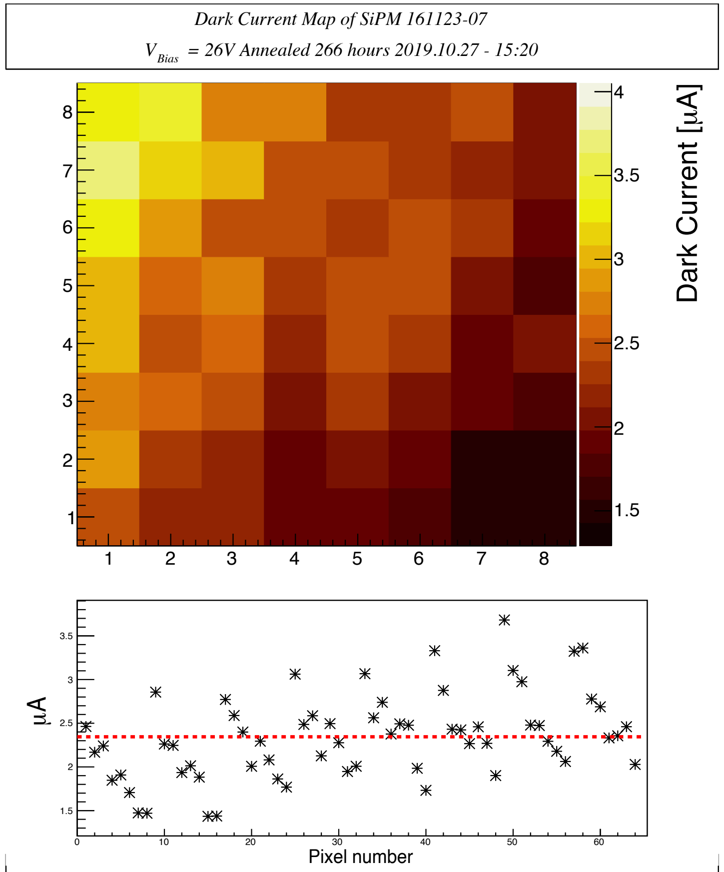
  I) Dark current characterization

  II) Responsivity characterization

V) Summary and Outlook

SUMMARY AND OUTLOOK

- An experiment was conducted by irradiating a healthy SiPM array to understand the effects of radiation of the SiPM array
- Annealing of the SiPM array at room temperate and high temperature.
- An instrument was built to measure the integrity of the SiPM array and optimised.
- Detailed report of dark current or responsivity in the form of PDF will be produced in less than 30 minutes per SiPM array.
- This instrument was built for SensL ArrayJ 30020 8x8.
- It can be easily scaled to perform characterisation of larger or smaller SiPM arrays. Parameters in the software should be scaled appropriately.



Total current = 150.065 μA

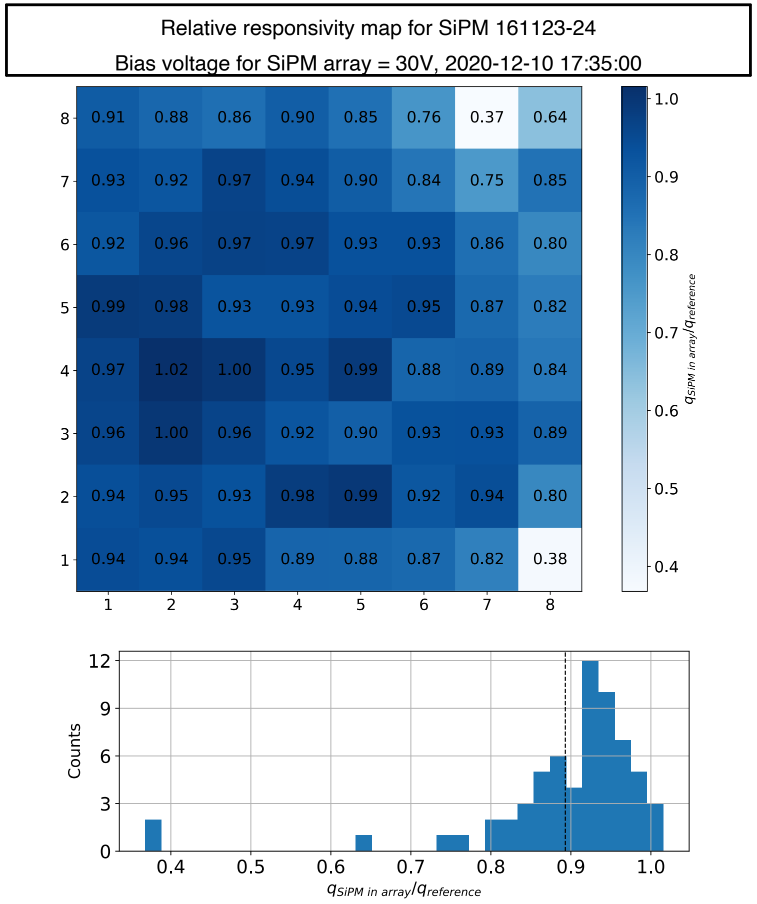
Average = 2.345 μA

RMS = 0.482 μA

Maximum Current = 3.682 μA @pixel 48

Minimum Current = 1.434 μA @pixel 14

THANK YOU



Highest count = 12 @ 0.92 relative charge

Average = 0.89

RMS = 0.90

Highest value = 1.02 @ SiPM [26]

Lowest value = 0.37 @ SiPM [63]

BACKUP

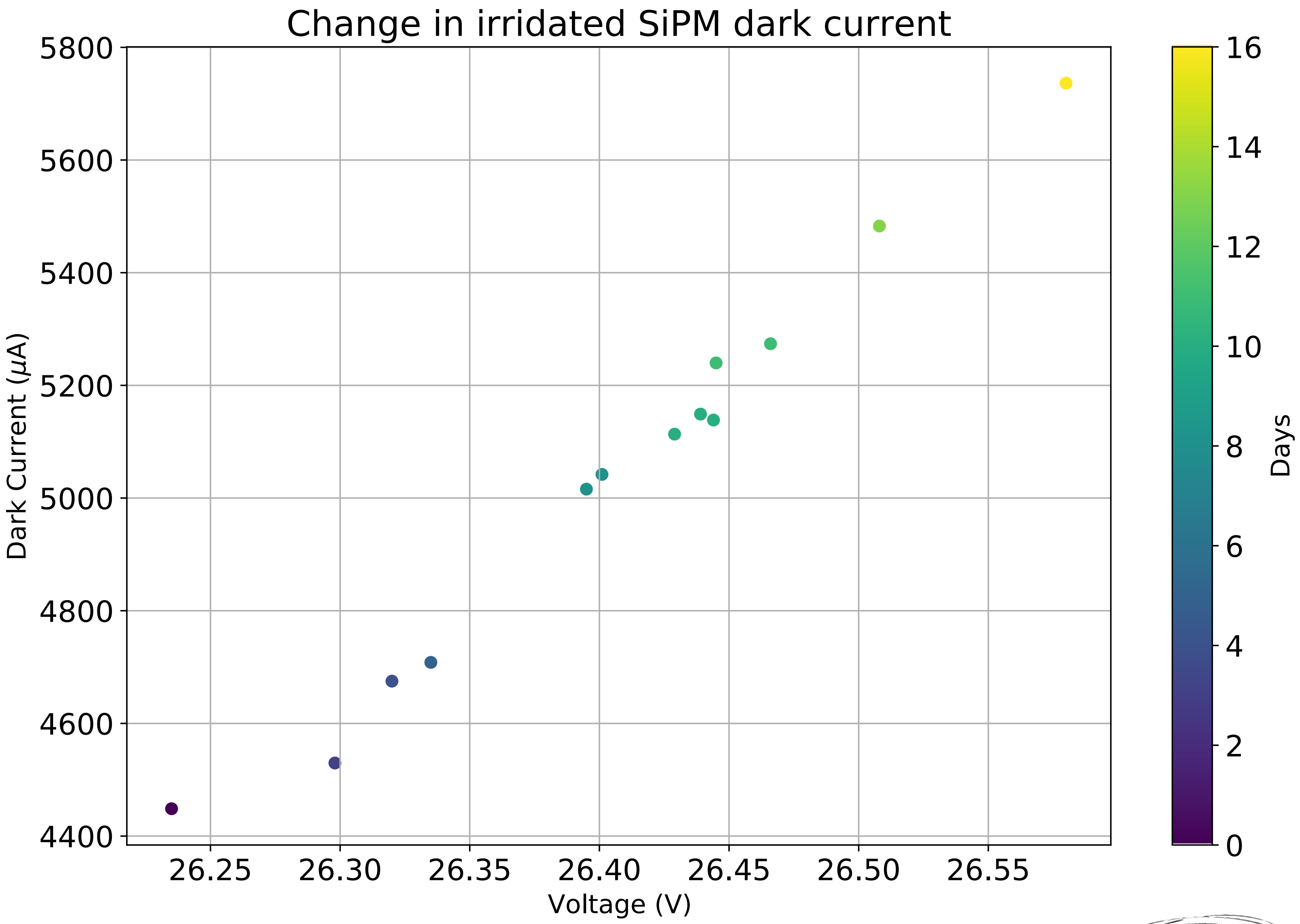
BACKUP

- The photon detection efficiency (PDE) is a measure of the sensitivity of an SiPM and is a function of wavelength of the incident light, the applied over-voltage.
- $P.D.E = \frac{R \cdot h \cdot c}{e \cdot \lambda \cdot G} \cdot 100\,\%$, where R is responsivity, G is gain and λ is wavelength, h is planks constant and c is the speed of light

- Responsivity is defined as the average photocurrent produced per unit optical power:-

$R = \frac{I_p}{P_{op}}$ = (measured photocurrent) / (incident optical power of wavelength)

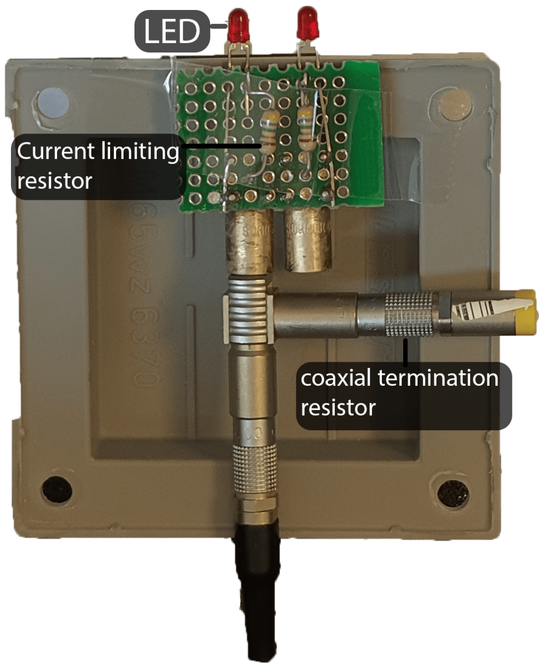
BACKUP

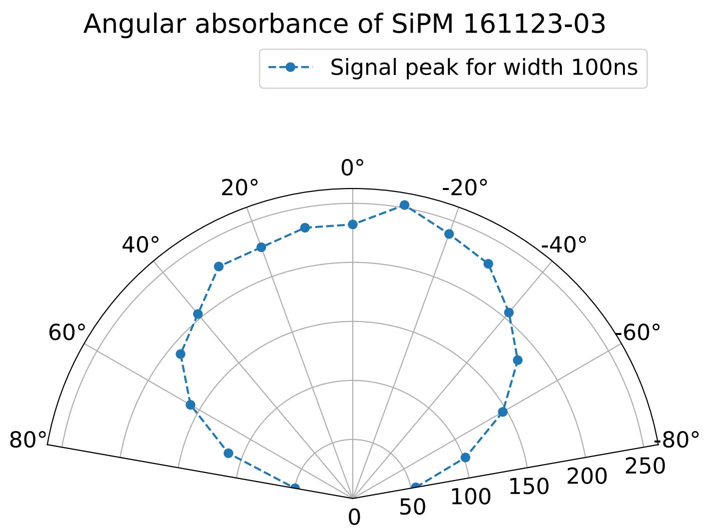


Change in irridated SiPM dark current
Dark Current (μA)
5800
5600
5400
5200
5000
4800
4600
4400
26.25
26.30
26.35
26.40
26.45
26.50
26.55
Voltage (V)
Days
0
2
4
6
8
10
12
14
16

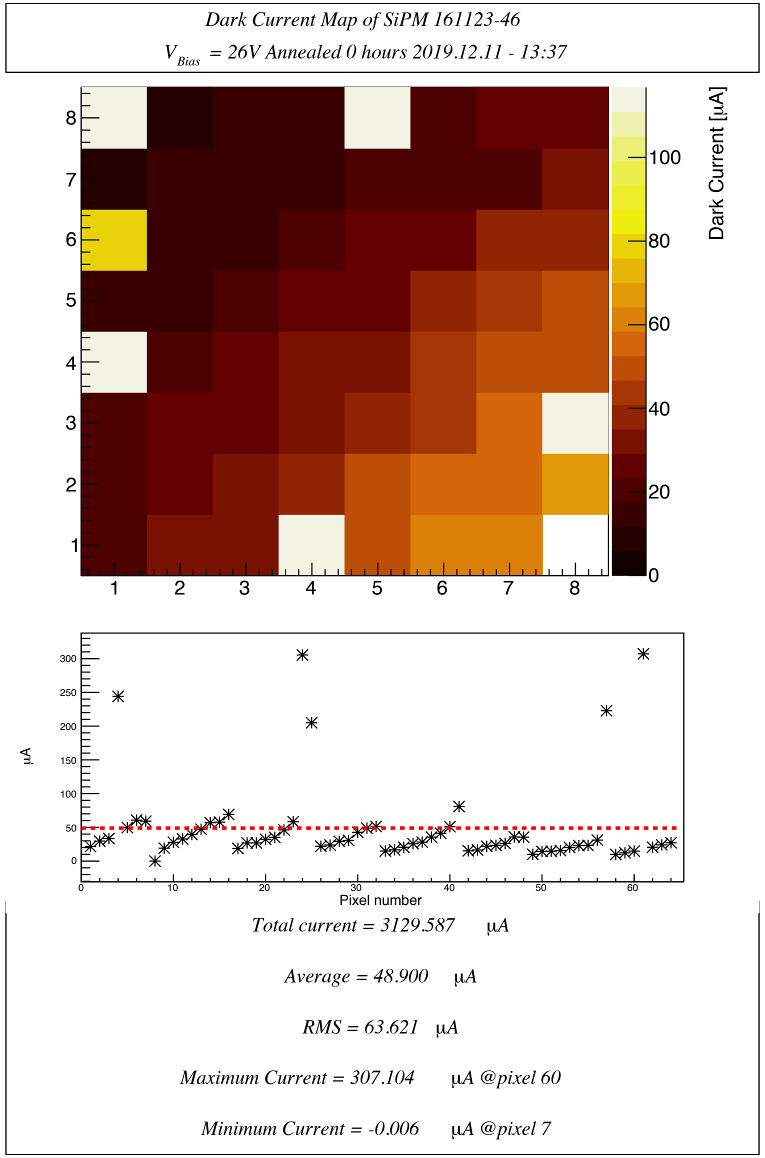
BACKUP

- The second LED reflected the light causing this kink at -10°





BACKUP



Dark Current Map of SiPM 161123-46
V Bias = 26V Annealed 0 hours 2019.12.11 - 13:37
Dark Current [µA]
0
20
40
60
80
100
1
2
3
4
5
6
7
8
µA
Pixel number
Total current = 3129.587 µA
Average = 48.900 µA
RMS = 63.621 µA
Maximum Current = 307.104 µA @pixel 60
Minimum Current = -0.006 µA @pixel 7

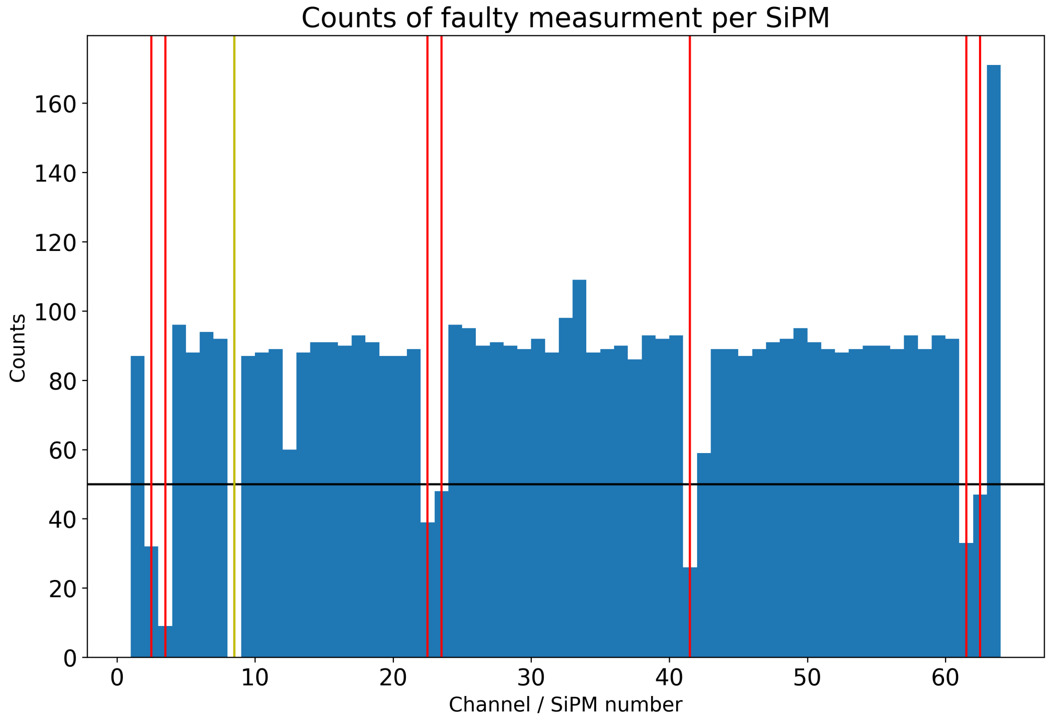
BACKUP - CURRENT ISSUES

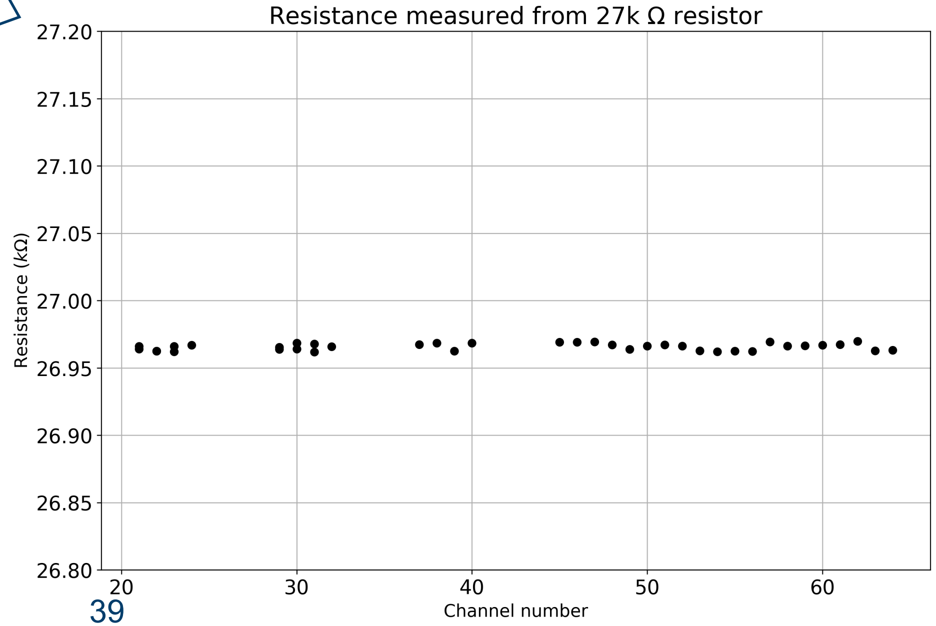
- Random jumps in the current recorded
- No pattern has been found yet

✳Calibration of the setup was performed by replacing SiPM board with 27kΩ resistor

Voltage and current were measured at all times. Resistance of the resistor was calculated using

$$R = \frac{V}{I}$$





- Measuring dark current of the whole matrix gives comparable results but not individual SiPM results

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