Test of SiPMs for the EIC calo project - May 2023 Update

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1 Experimental setup

The experimental setup is similar to the one described in the previous SiPM linearity measurement report. A few notable changes have been made.

The LED light is now sent to an integrating sphere that spreads the light over a large surface of several mm^2 as shown in Fig. 1. This is used to ensure that the light will be uniformly spread when testing larger SiPMs with a surface of $6 \times 6mm^2$. This is also used because it was realised that the filters that are put in front of the LED light can deviate the beam, and cause filter calibration to become tedious when using more filters, as described in the following procedure 1.1. Having a wide spread beam allows to have deviation of the beam by a few mm without impacting the LED flux on the SiPM. A control PMT is placed on the other side of the integrating sphere and is used to monitor the LED flux variations. The setup is presented in Fig. 2.

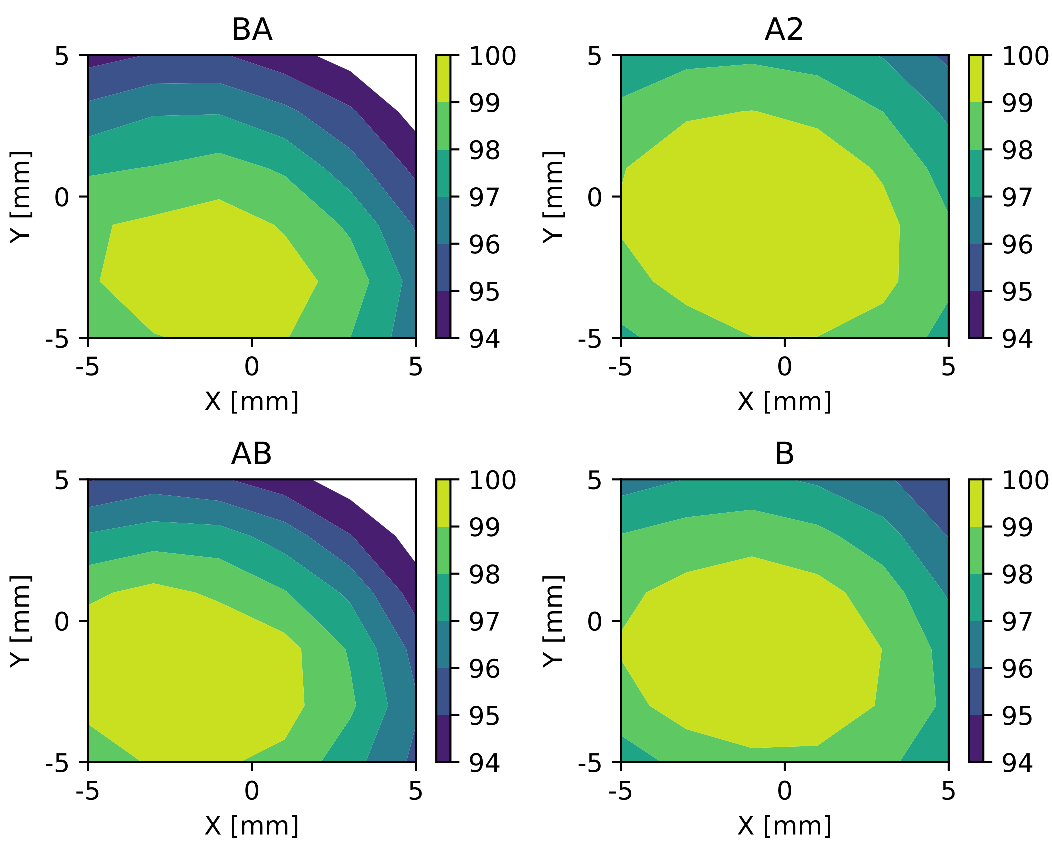

Figure 1: Light intensity on a 100 mm^2 surface with different filter configurations (see Section 1.1 for a description of the configurations)

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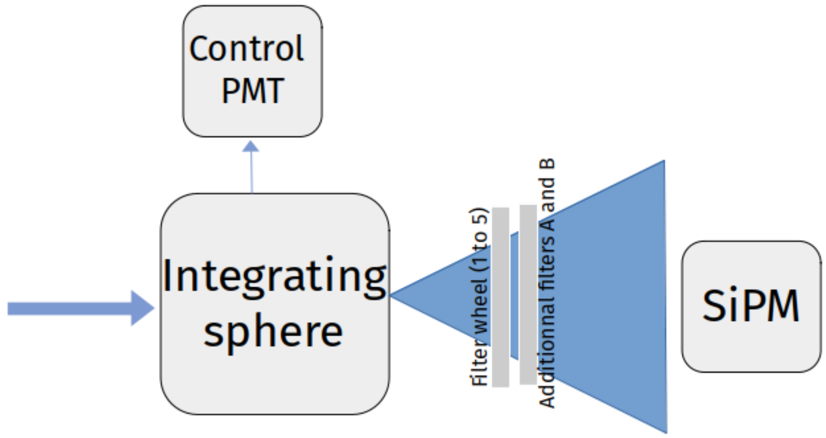

Figure 2: Setup schematic

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1.1 New strategy and filter calibration

In previous measurements, 3 different filters were used to access a relatively restricted dynamic range (there was a factor $\simeq 10$ between the lightest and densest filters), before having to increase the input LED light. To avoid bias from this method, and to allow for more intermediate measurements to be done, a new strategy is now used. A filter wheel containing filters labeled 1 to 5, and a hole with no filter, is placed in front of the LED. Additional filters, labeled A and B, can be placed additionally in front of the filter wheel.

Figure 3: Filter wheel with the 5 filters that are used during the measurement. Position 6 has no filter.

The filter calibration can be found in Table 1. As before, the density filters have been calibrated using a photo-diode which can be placed in front of the LED, in place of the SiPMs. Light is sent through the filters to the photo-diode which current is read. The relative attenuation between all filters is estimated using the ratio of the photo-diode output currents. The factor between the lightest and densest filters is now $\simeq 4800$ with 24 possible data points.

filter configuration	$\frac{\text{output current}}{\text{output with config AB5}}$	filter configuration	$\frac{\text{output current}}{\text{output with config AB5}}$
A+B+5	1.0	A+5	124.9
B+5	1.3	5	160.8
A+B+4	1.8	A+4	224.1
B+4	2.2	4	288.6
A+B+3	2.9	A+3	359.4
B+3	3.7	3	462.6
A+B+2	11.6	A+2	1492.0
B+2	14.8	2	1920.5
A+B+1	19.5	A+1	2547.0
B+1	25.0	1	3264.1
A+B	29.0	A	3761.9
B	37.2	no filter	4836.9

Table 1: Filter calibration

2 Linearity measurement

The linearity is measured by measuring the SiPM output current directly from their power supply. At the beginning of each experiment, a measurement with the SiPMs in the dark is made to estimate the dark current. It is considered as an offset and subtracted from all current measurements in the following. Details about this measurement can be found in Section 3.

The LED light is driven by 200ns pulses. The expected number of photo-electrons is the number of photo-electrons in configuration “AB5” multiplied by the factor in table 1. The measured number of photo-electrons can be inferred from the measured current I by :

$$\text{measured number of pe} = \frac{I}{\text{LED frequency} \times \text{gain} \times q_e} \tag{1}$$

Fig. 4 shows a comparison with the statistical expectation, derived from [1]:

$$\text{number of pe from stat. derivation} = N_{pixel}(1 - exp(-\frac{\text{expected number of pe}}{N_{pixel}})) \tag{2}$$

To quantitatively assess deviation from linearity, we can compute the linearity as:

$$\text{linearity} = \frac{\text{expected number of pe} - \text{measured number of pe}}{\text{expected number of pe}} \tag{3}$$

Results are shown in Fig.5. The region of interest is the region up to the maximum number of photo-electrons expected in the EEEMCal : 4500 (resp. 6000) for the 10 μm (15 μm) SiPMs. Results are shown in Fig.6.

Systematic effects can clearly be seen between the very low number of photo-electron region and the rest of the data. This could be due to several effects. A possible explanation, discussed more lengthily in Section 4 could be that manipulating the additional filters A and B often present a risk of getting them dirty. Another effect could be that the calibration of the densest filters relies on the response from the photo-diode which is considered ideal, which might not be the case for low signals. The normalisation for the number of photo-electrons is then difficult as the first points are systematically lower than the following, and as we can not assume a linearity of 1 when the number of photo-electrons increases. For this reason, we consider that the linearity can be known up to 4%.

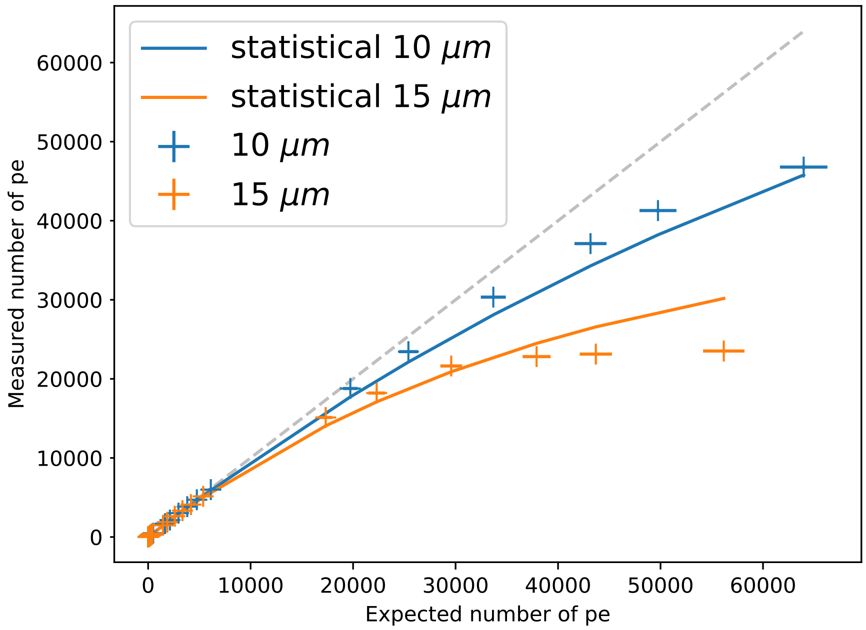


Figure 4: Measured number of photo-electrons compared to the expected number of photo-electrons if the SiPMs were perfectly linear

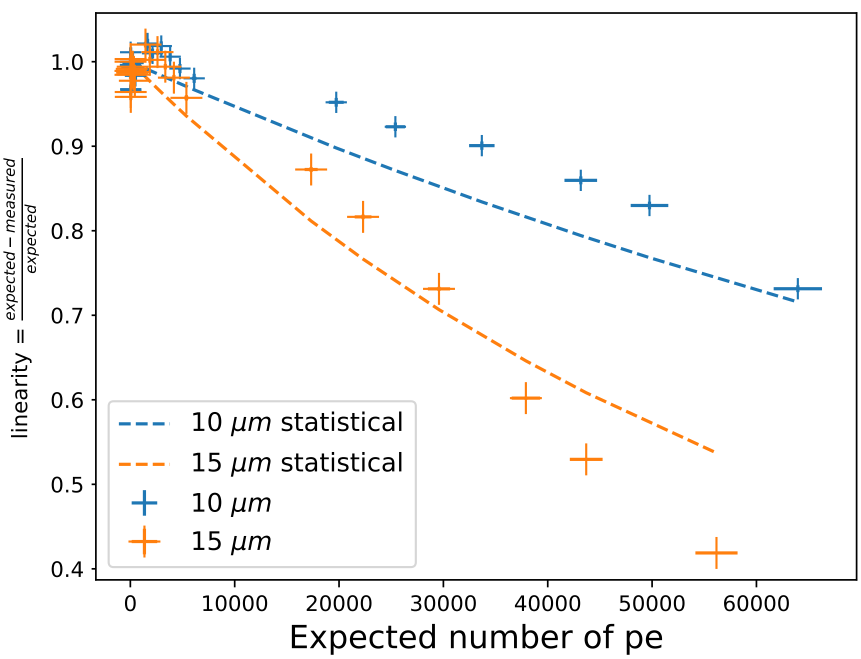


Figure 5: Linearity measurement with a 200ns pulsed LED

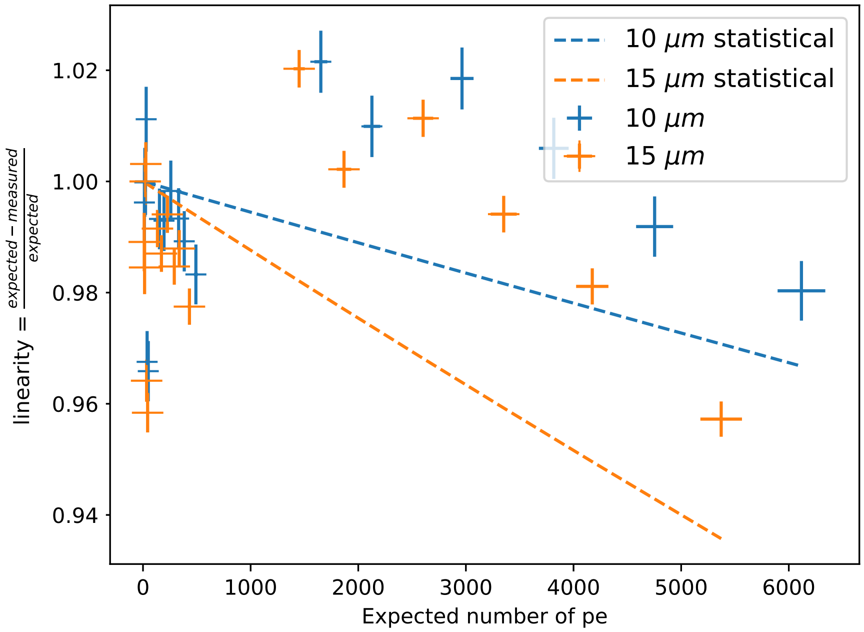


Figure 6: Linearity in the region of interest for the EEEMCal

3 Dark noise variations in time

The SiPMs were placed in the dark and their current was measured every second for several minutes after polarizing them, to study the drift in the dark noise with time. Results are shown in Fig. 7: after a few minutes, the dark current stabilizes and variations stay under 1%. This is used to estimate the error on the dark current as the standard deviation of the distribution of measurements done after stabilization of the dark current.

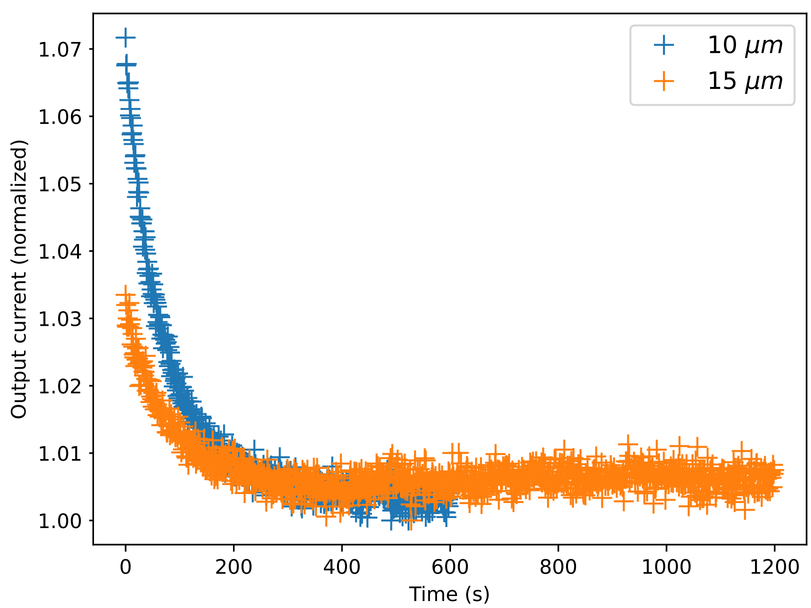


Figure 7: Evolution of the dark current after polarizing the SiPMs.

4 Alternative filter calibration

The calibration presented in Table 1 was done taking measurements with all filters between the LED and the SiPM to try and take into account all variations coming from the addition of filters. However, this necessitates removing the filters from the filter mount and putting them back, with a risk of getting them dirty with dust or fingerprints. This would in particular have an important impact on filter B which has a low transmission of 0.7%. To eliminate this effect, we can make the hypothesis that the spatial deviation from the addition of a filter is negligible when using the integrating sphere, and that transmissions of all filters multiply. We would therefore only need to calibrate filters 1 to 6 and A and B individually and multiply their transmission to get the full calibration presented in Table 2.

filter configuration	$\frac{\text{output current}}{\text{output with config AB2}}$	filter configuration	$\frac{\text{output current}}{\text{output with config AB2}}$
A+B+5	1.0	A+5	130.2
B+5	1.3	5	167.4
A+B+4	1.8	A+4	233.6
B+4	2.3	4	300.3
A+B+3	2.9	A+3	374.4
B+3	3.7	3	481.4
A+B+2	11.9	A+2	1554.5
B+2	15.4	2	1998.8
A+B+1	20.3	A+1	2642.1
B+1	26.1	1	3397.1
A+B+6	30.1	A+6	3915.2
B+6	38.7	6	5034.0

Table 2: Alternative filter calibration

With this new calibration, results for the linearity are shown in Fig 8. The systematic effect seems to be reduced, but we still have a discrepancy with measurements using a low number of photo-electrons that is not fully understood.

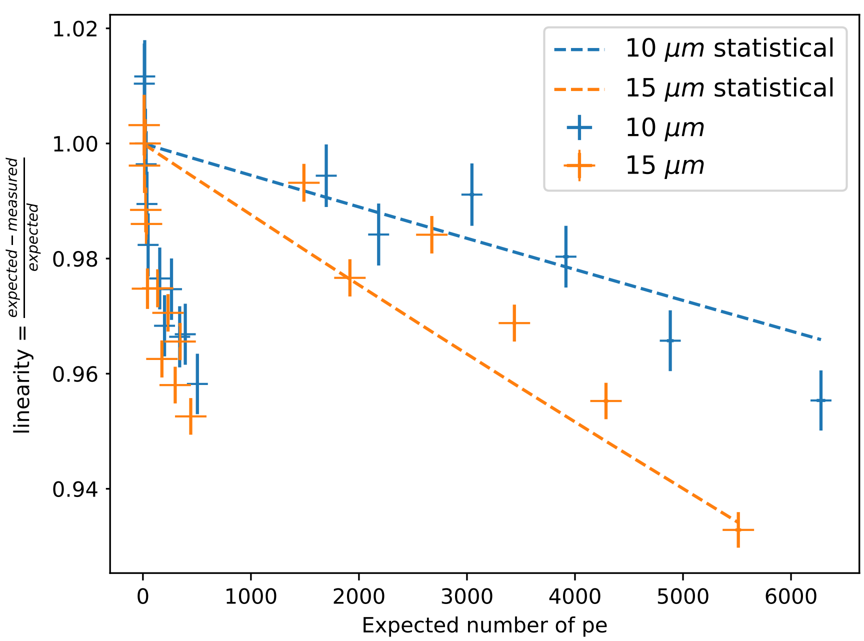


Figure 8: Linearity with the alternative filter calibration

5 Tests with $6 \times 6mm^2$ SiPMs

S14160-6015 SiPM were tested.They allow to polarize and readout the equivalent of 4 of the 3010/3015 models at the same time, reducing the number of readout channel by 4. The soldering process is more complicated. Four pins (anode, cathode, and two have no connection) and a thermal paddle are found at the back of each SiPM, as can be seen in Fig. 9. In this figure, the pins at the back of the SiPMs have been broken during or soon after they have been soldered.

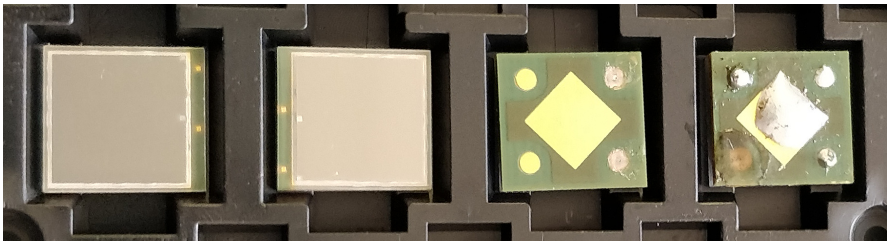
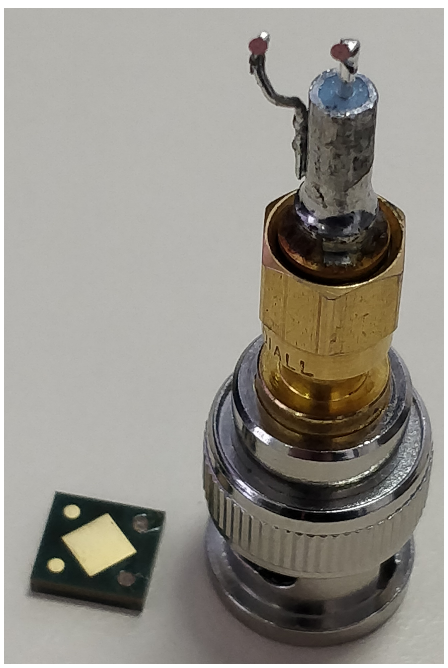
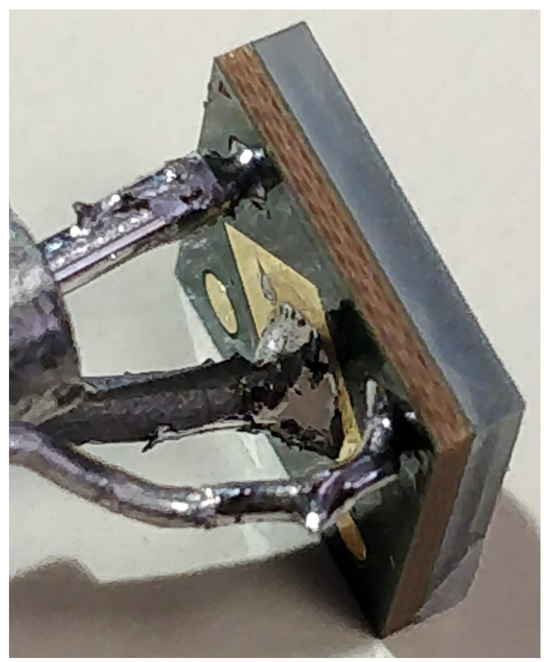


Figure 9: S14160-6015 SiPM

The pins' small surface makes them fragile, and even a light mechanical effort on a wire connected to a pin can tear off the gold layer covering them as seen in Fig. 10a. Tests were done as in Fig. 10b to try and improve the mechanical support of the soldering by connecting the thermal pad to ground with a thicker wire. The difficulty now arose from creating short circuits since having fine welds close to each other is difficult "by hand". A small PCB matrix should be designed to readout these SiPMs and continue measuring their performances.



(a) Broken connection



(b) Test to improve mechanical support

Figure 10: Soldering tests for S14160-6015 SiPMs

A measurement of the SiPMs linearity could still be done with this model. The single photo-electron spectrum, and thus the gain, could not be measured before breaking the SiPMs.
To try and reduce the systematic effects seen in the previous measurement, the filters were re-calibrated exchanging configurations to avoid having to calibrate very low light levels with the diode. The new calibration is presented in Table 3. The dynamic range that can be covered this time is reduced to a factor $\simeq 420$, with still 24 possible data points.

filter configuration	$\frac{\text{output current}}{\text{output with config AB2}}$	filter configuration	$\frac{\text{output current}}{\text{output with config AB2}}$
6	417.9	B+3	16.1
A+6	327.0	5	14.2
1	284.3	A+B+3	12.7
A+1	222.6	A+5	11.1
B+6	164.9	B+4	10.1
A+B+6	129.9	A+B+4	7.9
B+1	112.2	B+5	5.6
A+B+1	88.6	A+B+5	4.4
3	40.7	2	3.3
A+3	31.9	A+2	2.6
4	25.4	B+2	1.3
A+4	19.9	A+B+2	1

Table 3: Filter calibration for the linearity measurement of the S14160-6015 SiPM

Results for the number of measured photo-electrons compared to the expected number of photo-electrons are shown in Fig. 11.

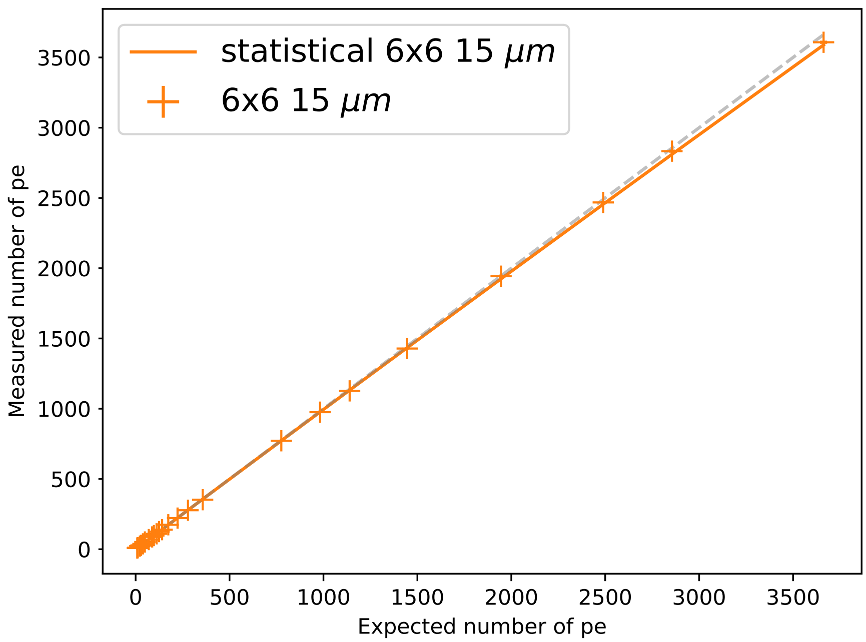


Figure 11: Measured number of photo-electrons for the S14160-6015 as a function of the number of photo-electrons expected if the SiPMs were perfectly linear

Results of the linearity measurement can then be found in Fig. 12. Note that since no measurement of the gain could be done, the gain is taken from the data sheet provided by Hamamatsu, without an estimation for its error. The systematic effect seems to be reduced with this eased calibration process, but is still present and measurement below several % for the linearity are not possible with the current setup.

In that range, the SiPMs appear to be linear to more than 99%. This range is however very limited compared to the one needed for the detector, since we expect 24000 photo-electrons at 15 GeV for this model of SiPMs.

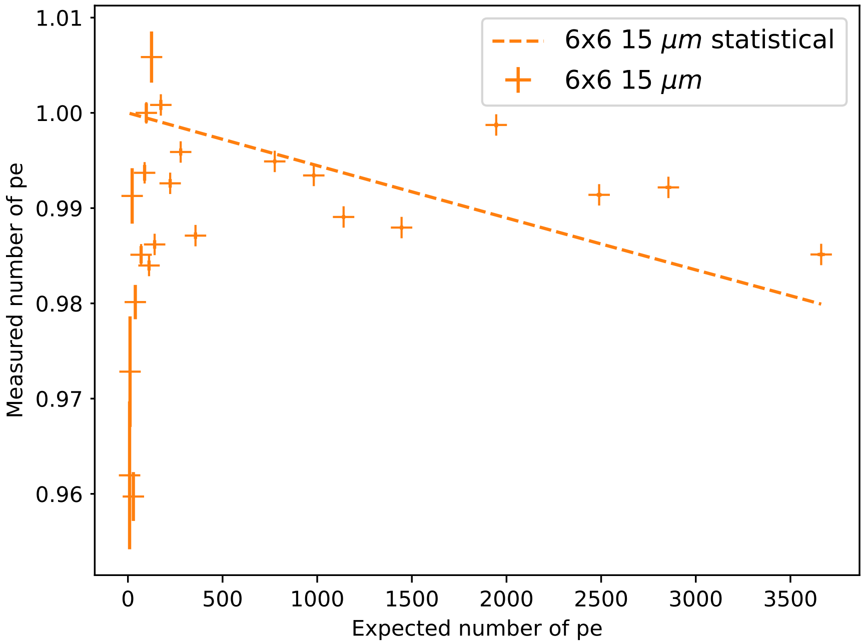


Figure 12: S14160-6015 linearity measurement

References

[1] Hamamatsu. MPPC technical note.