Test of SiPMs for the EIC calo project

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Abstract

Within the context of R&D for the EPIC Electron-Endcap Electromagnetic Calorimeter at the EIC, SiPMs with a large dynamic range are needed in order to detect particles ranging from 50 MeV to 15 GeV. We report for linearity performances of Hamamatsu S14160-3010 and S14160-3015 SiPMs. Challenges come from their low gain of the order of 10^5. For the 3010 (resp.3015) models, between 15 (20) and 4500 (6000) photo-electrons need to be detected, and linearity is expected to be better than 97% (90%) in that range.

1 Context

The EPIC Electron-Endcap Electromagnetic Calorimeter (EEEMCal) will be composed of bars of $PbWO_4$ crystals read by photodetectors. A possibility is to use SiPMs, which have the important advantage of being operational under the expected magnetic fields in EPIC. The main criteria for choosing a model of SiPMs for this application is their dynamic range, since particles ranging from 50 MeV to 15 GeV need to be detected in the EEEMCal. SiPMs with a large number of pixels are therefore studied, in particular the S14160-3010 and S14160-3015 Hamamatsu models are considered[1]. They both use the same technology, with different numbers of pixels. The former has 89984 $10\mu m$ pixels while the latter has 39984 $15\mu m$ pixels. In this document, we present measurements for their linearity over the range of energies needed for the EEEMCal.

2 Experimental setup

SiPM are tested individually. A SiPM is fixed on a translation table in front of a LED light ($\simeq$ 420nm). The translation table allow fot the SiPM to be moved along the axis between the light and the SiPM (z) and the horizontal/vertical axes (x/y). The light is driven by a pulse generator. A beam splitter sends half of the light to the SiPM, and half to a control PMT to ensure that the LED light did not vary significantly during measurements. Optical density filters can be placed between the LED and the SiPM. They have been calibrated as described in section 2.2. The entire setup is placed in a black box. The SiPM is polarised with a Keithley source meter unit.

Depending on the measurement, the SiPM output current or charge can be measured. The SiPM are read by a short coaxial cable of less than 1 cm, as shown in Fig. 1. The current is directly read using the source meter unit.

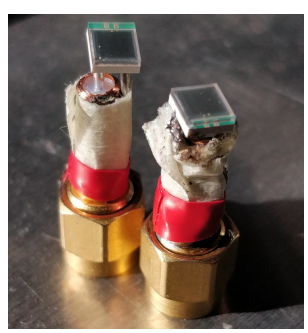


Figure 1: SiPM connection with a short coaxial cable and an SMA connector

An additional electronic setup is used for charge measurements as described in Fig. 3. A 140 MHz low pass filter is used to reduce noise before the signal is amplified $\simeq 227$ times (see section 2.1 for details on the amplifier calibration). Both the low pass filter and the amplifier are needed since signals for a few photo-electrons are low, due to the gain of the SiPMs which is of the order of 10^5. The signal is finally read with an oscilloscope, that is triggered on the pulse generator signal that drives the LED.

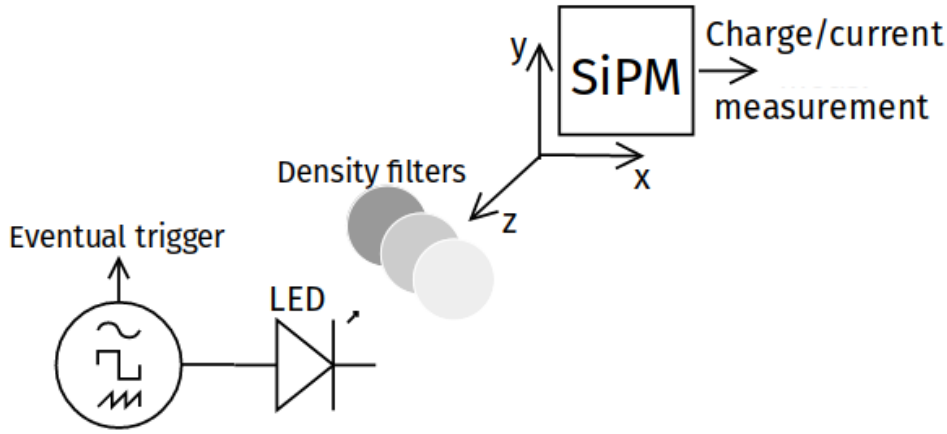


Figure 2: General setup used for SiPM tests with a LED.

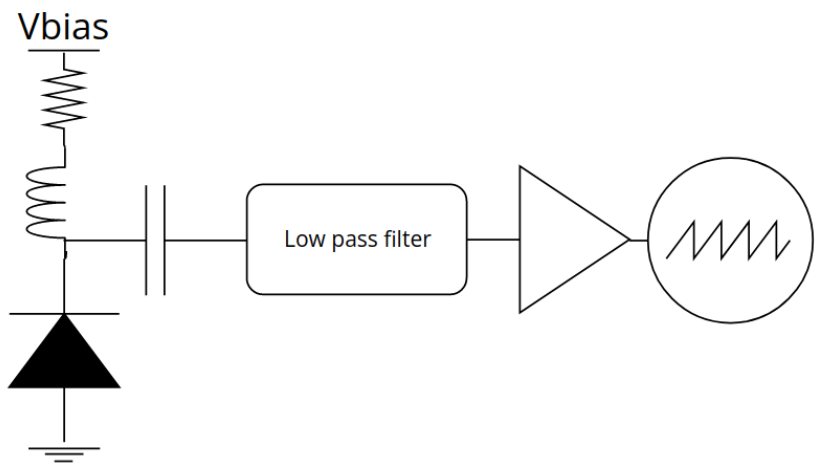


Figure 3: Circuit for the charge measurement

For all the measurement presented in this document, SiPMs are operated at the voltage recommended by Hamamatsu. Their temperature is not controlled.

2.1 Amplifier gain calibration

The amplifier gain was calibrated with a simple setup. A pulse generator provides a signal of known amplitude, that is sent to a variable power attenuator, and to the amplifier. The output voltage is read with an oscilloscope. Measurements were repeated 7 times for various attenuation levels, to estimate uncertainties. The result is taken as the average of all measurements, and the error as $\frac{\text{max measurement} - \text{min measurement}}{2}$, giving $g_{ampli} = 227.3 \pm 0.7$.

2.2 Optical density filters calibration

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. Filters are numbered from 1 to 3, 3 being the densest. The relative attenuation between all filters is estimated

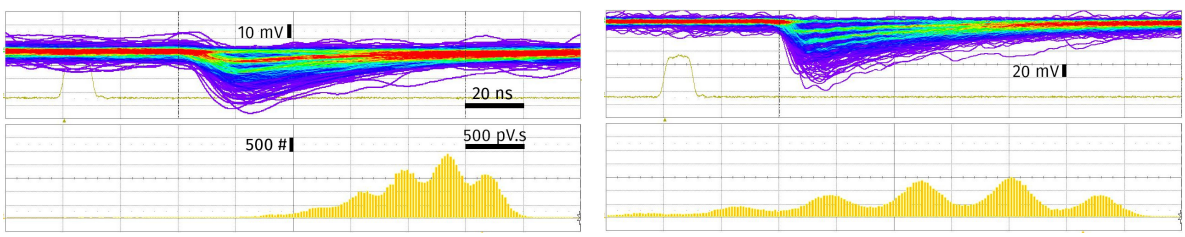
using the ratio of the photo-diode output currents. The error on that measurement was estimated repeating it 4 times and taking the error as $\frac{\text{max measurement}-\text{min measurement}}{2}$. Measurements were done with different LED intensities, driving the LED either with pulses or in continuous mode.

filter	$\frac{\text{output current}}{\text{output with filter 3}}$	uncertainty
3	1	
2	4.12	0.06
1	8.12	0.03
none	10.42	0.02

Table 1: Filter calibration

3 Gain measurement

The gain of the SiPMs was measured using their single photo-electron spectrum. We are using the charge measurement described in section 2. Charge integration is done with the oscilloscope as shown in Fig. 4, using an additional internal low-pass filter of 200 MHz.



(a) 10 μm (b) 15 μm

Figure 4: Wave-forms and charge integration histograms from the SiPMs.

The photo-electron spectrum is fitted with a sum of gaussian distributions. All widths and norms are free parameter. The means of the pedestal and first photo-electron peak gaussians are free parameters. The mean of all other peaks is computed using the difference of these two first means $\Delta(1pe - \text{pedestal})$, that corresponds to a single photo-electron. The results are presented in Fig. 5. The gain is extracted from the charge of a single photo-electron, $Q_{1pe} = \frac{\Delta(1pe-\text{pedestal})}{R_{oscillo}}$:

$$\text{gain} = \frac{Q_{1pe}}{g_{ampli} \times q_e} \tag{1}$$

4 Linearity measurement

Once the SiPM gain is known, linearity can be studied measuring the SiPM output current directly from the power supply. The LED is driven by a square pulse of 20ns.

The number of photo-electrons can be inferred from the measured current I by :

$$\text{measured number of pe} = \frac{I}{\text{LED frequency} \times \text{gain} \times q_e} \tag{2}$$

The experimental protocol is as follow :

- Step 0 : Place the densest filter (filter 3) and adjust the LED intensity so that the output SiPM current is significantly higher than the dark current but within a range where the SiPMs are expected to be linear. In this study, the intensity was adjusted so that around 17 photo-electrons were detected.

- Step 1 : Measure the current for filter 3, 2, 1, and with no filter. Each time, the expected current/number of photo-electrons can be estimated from the number measured with filter 3 and the filter calibration from Table 1.
- Step 2 : Place filter 3 back. Increase the LED intensity so that the output current matches the one that was reached at the end of step 2 with no filter. Repeat step 1.

The linearity is then computed as :

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

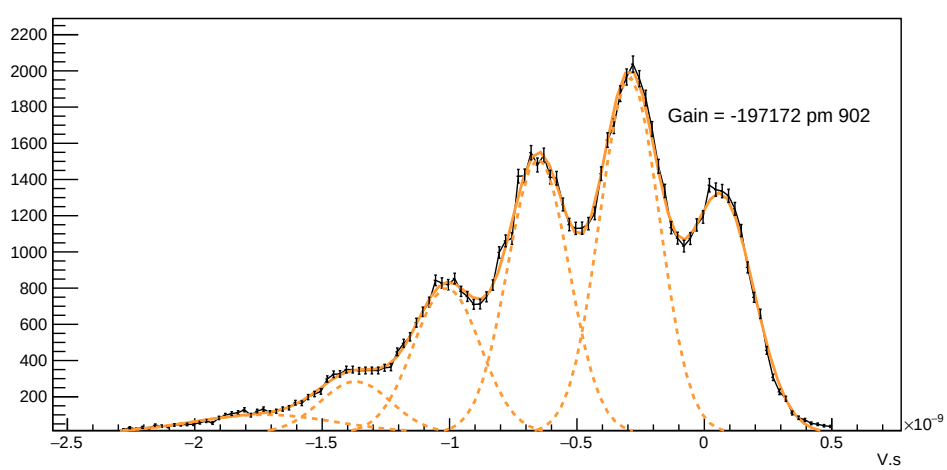
In Fig.6, the linearity is plotted as a function of the expected number of pe. It is compared to the theoretical expectation, derived from [2]:

$$\text{theoretical number of pe} = N_{pixel}(1 - exp(-\frac{\text{expected number of pe}}{N_{pixel}})) \tag{4}$$

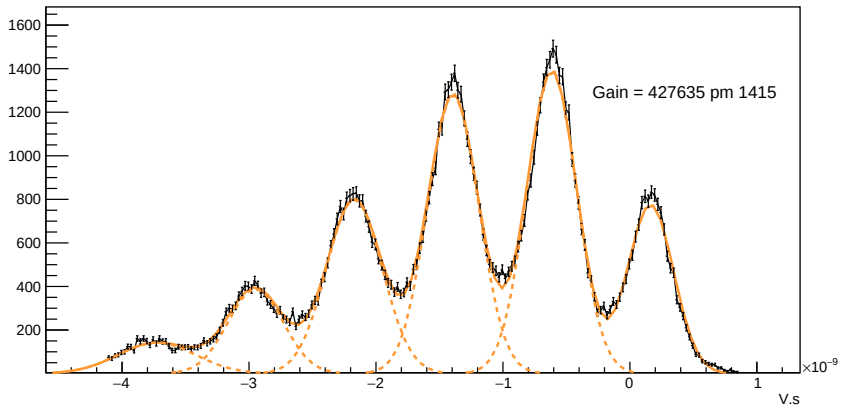
The $10\mu m$ SiPM is linear up to 98% in the range of 16 pe to at least 1769 pe, and up to 95% at least up to 7305 pe. The $15\mu m$ SiPM is linear up to 98% in the range of 18 pe to at least 769 pe, and up to 95% to at least 1939 pe. The measured linearity is lower than the theoretical expectations in both cases when getting far from the linear regime. This could be due to local saturation of the SiPM, since the LED flux was only vaguely checked to be homogeneous. Measurements will be done again ensuring that the SiPMs are placed in a region with homogeneous flux. The 20ns pulses are shorter than the expected pulses from PWO. With larger pulses, pixels can recover and linearity can increase. A quick measurement was done with a continuous flux of light on the SiPMs and are presented in Fig. 7. This measurement needs to be repeated with proper error estimation, but this first result seems to indicate that the linearity of both models is over 95 % over 4 orders of magnitude in a continuous flux. Simulations of the timing information coming from production and propagation of the scintillation photons inside the PWO barrel could be useful, to understand what shape should be given to the test LED pulses in order to produce linearity measurements in realistic conditions.

5 Quick comparison between the number of photo-electrons and the detected energy

Previous measurements of PWO bars light yield were made, and 17 pe/MeV were estimated to be produced over the 4 cm^2 section of the bars, with a PMT which quantum efficiency was 25%.



(a) 10 μm



(b) 15 μm

Figure 5: Single photo-electron spectrum, fitted with a sum of six gaussians.

pixel size (μm)	LY per SiPM	Number of pe at 50 MeV	Number of pe at 15 GeV
10	0.3	15	4500
15	0.4	20	6000

Table 2: Estimation of the LY and number of pe range

A PDE of 18% is considered for the 10μm pixels SiPM, and of 27% for the 15μm pixels SiPMs. Their surface is 9 mm^2. This allow for estimation of a light yield per SiPM, and the range in the number of pe that need to be detected between 50 MeV and 15 GeV, as shown in Table 2.

This computation is a rough estimate since the PDE of both SiPMs model vary with the wavelengths expected for scintillation photons from PWO (the spectra has several components between 420nm and 520nm) , as shown in Fig. 8.

Our setup demonstrates detection over all of this range is possible with the simple current measurement configuration. Fitting the linearity as a function of the expected number of pe with a linear function as shown in Fig. 9, we get that the 10 μm pixels SiPMs are linear at 97% at 15 GeV. The 15 μm pixels SiPMs have 90% linearity at that energy.

6 Conclusion and perspectives

Hamamatsu S14160-3010 and S14160-3015 linearity was measured in order to study their dynamic range. The main difficulty comes from gain estimation by measuring the single pe spectrum, since both models have low gain of the order of 10^5. Linearity measurements have been done with a pulsed LED over 3 orders of magnitude. A rough comparison with the light yield of PWO indicates that energies between 50 MeV and 15 GeV could be measured with a linearity of at least 97% with the 3010 model, and 90% with the 3015 model.

Short-term plan could be to perform more tests studying local saturation of the SiPMs, and study with more care the response to a continuous flux. Medium-term plan could be to adapt the present charge measurement setup for realistic tests with PWO crystals and radioactive sources or atmospheric muons. It could be to measure the SiPM PDE.

In all cases, an estimate for the timing of pulses expected out of the PWO bars would help in making the LED pulses realistic and study saturation in accurate conditions. Improving the mechanics of the test bench for fixing the SiPMs would help in controlling their position.

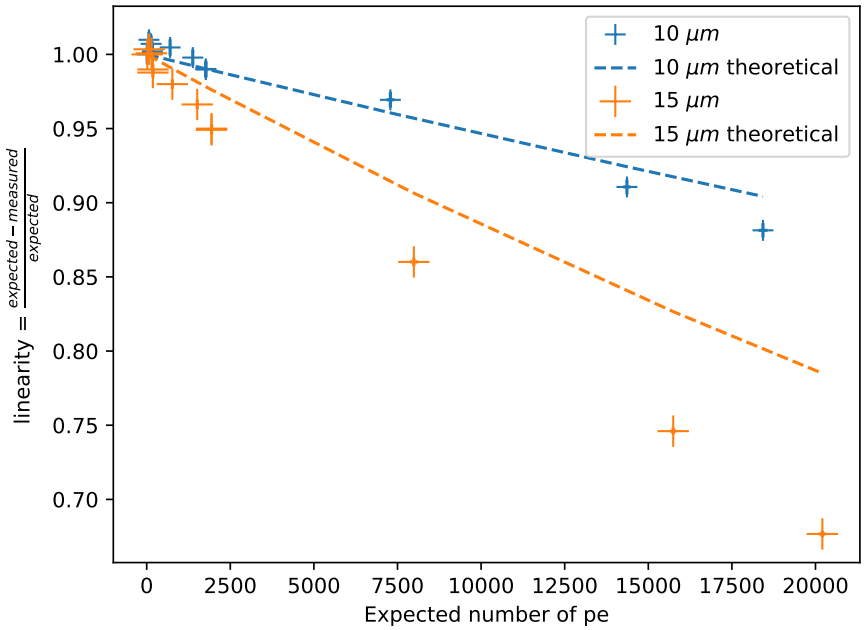


Figure 6: Linearity measurement with a 20ns pulsed LED

References

[1] Hamamatsu. S14-160 datasheet.

[2] Hamamatsu. MPPC technical note.

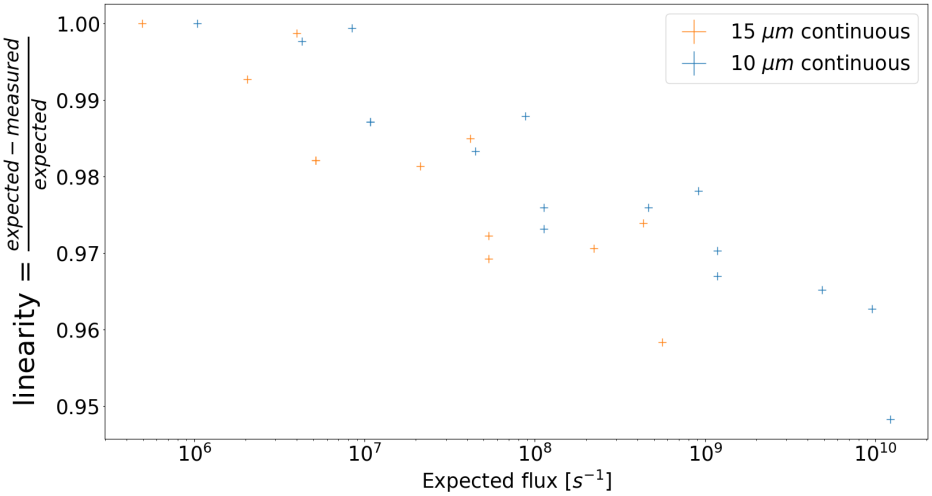


Figure 7: Linearity measurement with a continuously pulsed LED light.

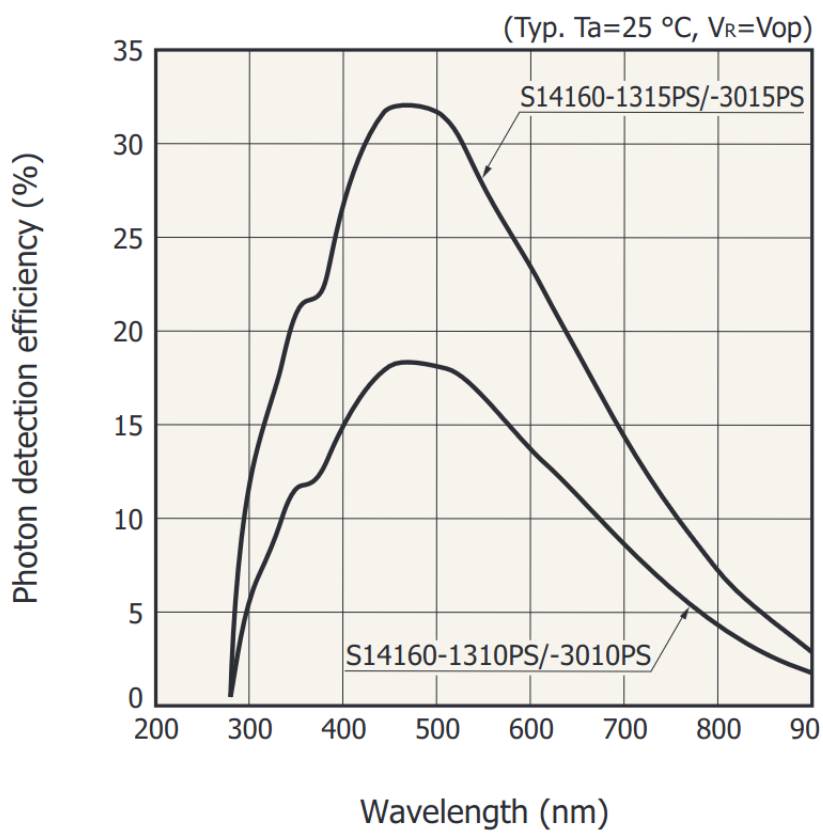


Figure 8: Photo-detection efficiency of the SiPMs at optimal voltage, directly extracted from [1]

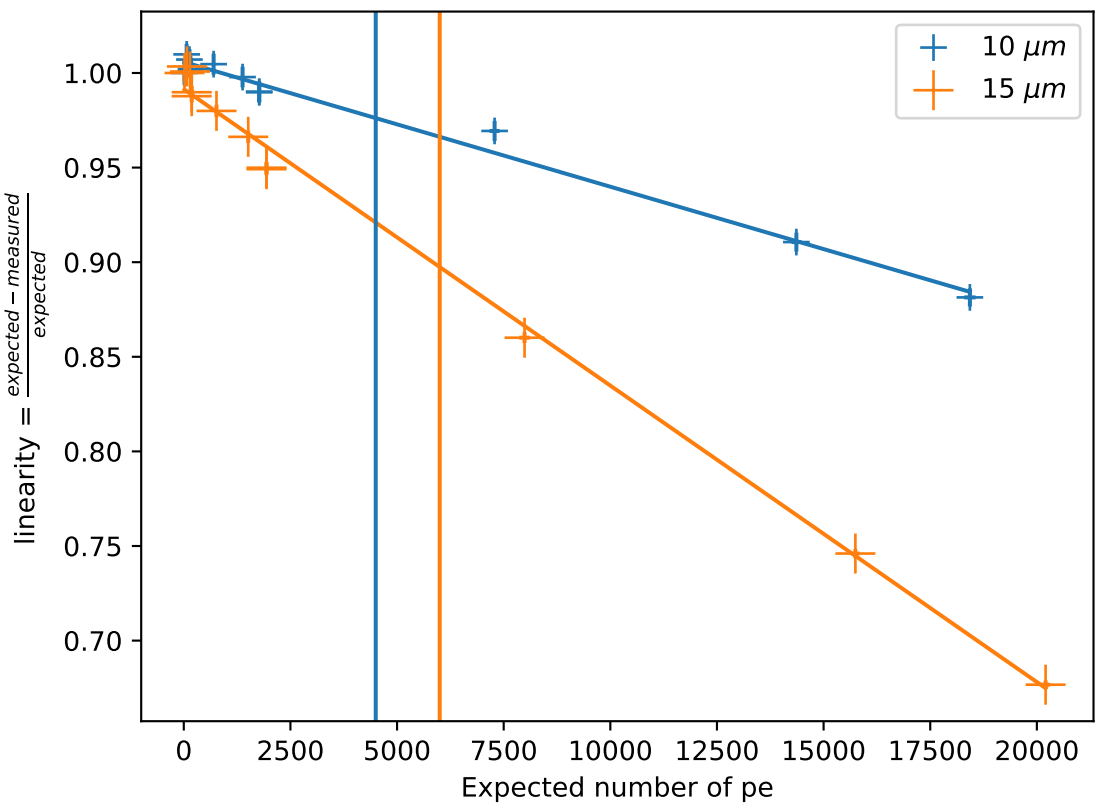


Figure 9: Linearity as a function of the expected number of pe, fitted with a linear function. Vertical lines highlight the number of pe expected as 15 GeV.