Characterisation of the Hamamatsu MPPC multichannel array for LHCb SciFi Tracker v.12.2015

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Abstract

In the context of the LHCb upgrade, the current Inner Tracker (silicon strip) and Outer Tracker (straw tubes) will be replaced with a single technology scintillating fibre tracker. The SiPM photodetectors used for the readout need to provide a high photon detection efficiency, low optical cross-talk, dense packaging and withstand a high neutron fluence. The batch of detectors, received in December 2015, was developed in collaboration with CERN and an SiPM manufacturer, Hamamatsu. This work was focused on the study of these devices and the evaluation of their performances. The measurements of breakdown voltage, cross-talk, dark count rate, photon detection efficiency and temperature dependence were performed and the effect of neutron radiation analysed. In summary: The peak PDE at $\Delta V = 3.5V$ is 47%. At $\Delta V = 3.5V$ the direct cross-talk is 4.5%, delayed cross-talk is 5.5% and after-pulse is 6.5%. DCR after a dose of $6 \times 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$ is 15MHz and is reduced a factor 2 every 10°C.
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1 Introduction

This document reports on the measurement of the properties of Hamamatsu 12.2015 S13552, called H2015. These detectors are multichannel arrays consisting in 128 channels. Each channel is composed of 104 pixels. LCT5 technology trenches are added to the detector for optical cross-talk suppression, which are only partially efficient (direct cross-talk \(\sim 5\%\) and delayed cross-talk \(\sim 6\%\) at \(\Delta V = 3.5V\)). Hamamatsu detectors from 2014, called H2014, are used as reference. H2014 is based on LCT3 technology (direct cross-talk \(\sim 17\%\) and delayed cross-talk \(\sim 1.8\%\) at \(\Delta V = 3.5V\)). The methods used to measure the properties of detectors will be presented in the appendix.

The properties that will be covered are:

- The geometrical aspect, footprint and packaging (Chap.2).
- The breakdown voltage (\(V_{bd}\)), for each channel (Chap.3).
- The temperature coefficient (Chap.4).
- The direct cross-talk, delayed cross-talk and after-pulse at different over-voltage (\(\Delta V\)) (Chap.5).
- The pulse shapes with timing constant (Chap.6).
- The gain current (\(G_i\)) and gain area (\(G_A\)) at different \(\Delta V\) (Chap.7).
- The quenching resistor (\(R_Q\)) at different temperatures (Chap.8).
- The photo detection efficiency (PDE) at different \(\Delta V\) (Chap.9).
- The dark count rate (DCR) after irradiation and annealing (Chap.10).
- The light yield at different \(\Delta V\) (Chap.11).

2 Geometrical aspect, footprint and packaging

Multi-channel Silicon Photo-Multipliers (SiPMs) from Hamamatsu are used to detect scintillation light from fibres. The channel pitch is 250 \(\mu m\) and the height is 1.62 mm. A channel contains 104 pixels of a size of 57.5 \(\mu m\) X 62.5 \(\mu m\). The detectors have 128 channels built out of two 64 channel silicon dies. Fig.(1) shows a picture of the packaging. A gap of 220 \(\mu m\) is present between the two dies. The SiPM package is mounted on a flex PCB which allows the read-out of each channel separately. A BGA soldering process with balls is used to solder the detector on the flex like in Fig.(3).

Figure 1: Picture under the microscope of the central channels of H2015 with the gap between the two dies.
3 Breakdown voltage

The voltage needed to start the avalanche is called the breakdown voltage ($V_{bd}$). Since it is strongly temperature dependent it is measured at 25°C or after measurement recalculated for 25°C. The over-voltage ($\Delta V$) is defined as:

$$\Delta V = V_{bias} - V_{bd} \quad (1)$$

For H2015, $V_{bd}$ typically changes by $\pm200$ mV within one array. H2015 has a lower $V_{bd}$ ($\sim 3$ V) compared to H2014. Both detectors show a similar pattern as seen in Figs. 4. A reduction of these fluctuations is not possible.  

1 Hamamatsu selects two chips with almost identical mean $V_{bd}$ for the array assembly. The fluctuations are most likely due to manufacturing fluctuations at the semiconductor processing, small differences of doping concentrations can produce electric field variations.
4 Temperature coefficient

The breakdown voltage of a SiPM is temperature dependent. A temperature increase will make the crystal lattice vibrations increase and slow down the charge carriers, reducing the probability of impact ionisation[1].

\[ V_{bd} \text{ is proportional to the temperature as shown in Fig.(5). For this technology the temperature coefficient is } 60 \text{mV/K (Fig.(6)). The spread is about } \pm 2 \text{mV/K over the 128 channels. Typical gain variation for } 1 \text{K at } \Delta V = 3.5 \text{V is } 1.7\%. \]

5 Direct cross-talk, delayed cross-talk and after-pulse

The pixel to pixel cross-talk is produced by infrared photons created during the avalanche. Opaque optical trenches between the pixels to reduce this effect. Cross-talk is proportional to the gain and thus to the pixel size. Two types of cross-talk can be distinguished:

Direct cross-talk Instantaneous and therefore fully correlated with a primary avalanche in a neighbouring pixel. The observation of the cross-talk signal shows nevertheless also small time delays between the primary avalanche and the cross-talk induced avalanche. The delay of a few 100ps reduces the peak amplitude of the sum of the two signals as it can be seen in Fig. 7. The signal amplitude observed is between 1 PE and 2 PE. Higher amplitude values are possible due to multiple
Figure 7: Illustration of direct and delayed cross-talk on the H2015 detector. On the left, only a few instantaneous (direct) cross-talk pulses are present. The amplitude of the sum of the initial noise pulse and the direct cross-talk pulse do almost never reach double amplitude. This can lead to underestimation of direct cross talk with an amplitude threshold based measurement. On the right, within a window of 200ns pulses with full 1 PE amplitude are recorded, these pulses are correlated to the initial dark pulse.

Figure 8: All pulse shape spectra selected with after-pulses (left) and delayed cross-talk (right) for H2015. The spectra were selected from a total of 2000 events with $\Delta V = 3.8$ V.

cross-talk but unlikely.\(^2\)

**Delayed cross-talk** Pulses delayed in time but with full amplitude. Strongly correlated with the primary avalanche. This type of cross-talk is the dominant correlated noise of H2015. The delay of the pulses is such that they are distributed over several 25ns intervals (LHC bunch crossing time). The signal amplitude is 1 PE.

**After-pulse** After-pulses (AP) are due to an avalanche in the same pixel as the primary avalanche. The pulse amplitude is given by the recovery state of the pixel. The AP probability is increased with a fast recovery time and a high $\Delta V$.

A signal comparison between direct and delayed cross-talk can be seen in Fig. 7.

To compare direct cross-talk, delayed cross-talk and AP we use a H2014 as a reference. For the H2015, direct cross-talk is strongly reduced (17% reduced to 4.5% at $\Delta V = 3.5$ V). On the other hand, delayed cross-talk and AP have significantly increased, beyond the 10% level at $\Delta V = 3.1$ V for the sum of both. Results for H2014 and H2015 are given in Table 1.

\(^2\)The probability of single cross talk in Fig. 7 is at 0.04 and double cross-talk at 0.0016.
Table 1: Direct cross-talk, delayed cross-talk and AP for different $\Delta V$. H2014 at $\Delta V = 3.1\, \text{V}$ is used as reference.

<table>
<thead>
<tr>
<th>$\Delta V$</th>
<th>0.8</th>
<th>1.3</th>
<th>1.8</th>
<th>2.3</th>
<th>2.8</th>
<th>3.3</th>
<th>H2014 (ref. at $\Delta V = 3.1, \text{V}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak amplitude [mV]</td>
<td>0.105</td>
<td>0.166</td>
<td>0.229</td>
<td>0.289</td>
<td>0.354</td>
<td>0.418</td>
<td>0.350</td>
</tr>
<tr>
<td>AP [%]</td>
<td>0.6</td>
<td>1.5</td>
<td>1.6</td>
<td>2.6</td>
<td>5.4</td>
<td>5.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Direct cross-talk [%]</td>
<td>1.9</td>
<td>1.2</td>
<td>1.6</td>
<td>2.8</td>
<td>3.3</td>
<td>4.1</td>
<td>14.2</td>
</tr>
<tr>
<td>Delayed cross-talk [%]</td>
<td>0.3</td>
<td>1.4</td>
<td>2.0</td>
<td>2.3</td>
<td>3.1</td>
<td>4.9</td>
<td>1.1</td>
</tr>
<tr>
<td>Sum [%]</td>
<td>2.8</td>
<td>4.0</td>
<td>5.1</td>
<td>7.6</td>
<td>11.7</td>
<td>14.7</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Noise clusters (NC) are typically produced by random or correlated overlap of several noise pulses within 25ns. Direct cross-talk leads to correlated noise and is therefore our dominant source of NC. AP and delayed cross-talk are distributed over several 25ns intervals, they don’t represent fully correlated noise and therefore produce lower noise cluster rate (NCR, defined in section ?? in appendix). NCR of the H2015 (for the same DCR) is expected to be significantly lower than for the H2014. Direct cross-talk also contributes to the signal and can therefore be accounted as an increase of light yield (LY). Delayed cross-talk and AP (arrive typically after the integration time) will produce spill-over (next or over-next bunch crossing). H2015 is expected to increase spill-over compared to H2014. AP, direct and delayed cross-talk dependencies on the $\Delta V$ can be seen in Fig. 9.

![Figure 9: PDE superimposed to the contribution of AP, direct cross-talk, delay cross-talk and the sum of the three for H2014 on the left and H2015 on the right.](image)

### 6 Pulse shape and recovery time

The pulse shape was characterised with an oscilloscope. The connection between the detector and the amplifier can suffer from parasitic inductance. The flex is equipped with two meshed ground planes. For the pulse shape measurements it is important to keep a low serial inductance transmission line between the SiPM and the pre-amplifier. The serial inductance was improved by an additional ground connection for the older versions of flex cables. The low inductance avoids random noise and ringing for the fast component of the signal. Typical pulse shapes can be seen in Fig. 10. The oscilloscope used has a 1 GHz bandwidth and the signal is amplified with a 2 GHz bandwidth amplifier. The fast pulse (short time constant $\tau_1 < 1\, \text{ns}$) is dominated by the acquisition bandwidth. The slow pulse component is fitted with an exponential. The long time constant ($\tau_2$) obtained is 40ns. To obtain the recovery time constant, the AP amplitudes are used (see Fig. 8). For H2015 the recovery time is 35ns (40% higher than for H2014).
<table>
<thead>
<tr>
<th>Time constant</th>
<th>H2014</th>
<th>H2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery time</td>
<td>25ns</td>
<td>35ns</td>
</tr>
<tr>
<td>Long component ($\tau_2$) at 25°C</td>
<td>30ns</td>
<td>40ns</td>
</tr>
<tr>
<td>Short component ($\tau_1$) at 25°C</td>
<td>&lt;1ns</td>
<td>&lt;1ns</td>
</tr>
</tbody>
</table>

Table 2: Summary of the time constant for H2014 and H2015.

Figure 10: Pulse shape for H2014 (left) and for H2015 (right). Note that a pre-amplifier was used (gain=107) and the $\Delta V = 3.5\,\text{V}$.

7 Gain

The gain corresponds to the number of electrons created when an avalanche is triggered by a photon. It is measured with two different methods. They are described in Ref. [4]. The current gain ($G_I$) is obtained through current measurement and the area gain ($G_A$) is obtained by integrating the area of signal pulses. Both $G_I$ and $G_A$ were measured for three channels. The comparison between $G_I$ and $G_A$ can be seen for different $\Delta V$ for both detectors in Fig. 11. The difference between $G_I$ and $G_A$ is increasing with $\Delta V$ for H2014. The difference can be explained by an incomplete quenching of the avalanche (too small recovery time). In the H2015 almost no difference is observed anymore. $G_I$ shows a linear increase with $\Delta V$. A constant offset is present between the two gains. The threshold scan for $G_I$ did not include all peaks lower than 0.5 PE (essentially AP) and lead to a higher gain. As expected the $G_A$ for H2015 ($3.25 \times 10^6 \,\text{e/ph at } \Delta V = 3.5\,\text{V}$) is higher compared to H2014 ($2.75 \times 10^6 \,\text{e/ph at } \Delta V = 3.5\,\text{V}$) because of the increased active pixel area (higher fill factor).

Figure 11: Mean $G_I$ and $G_A$ averaged over three channels as a function of $\Delta V$ for H2014 on the left and for H2015 on the right.
Table 3: $R_Q$ for odd and even channels at 25°C and 40°C.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$R_Q$ odd at 25°C [kΩ]</th>
<th>$R_Q$ odd at −40°C [kΩ]</th>
<th>$R_Q$ even at 25°C [kΩ]</th>
<th>$R_Q$ even at −40°C [kΩ]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>206</td>
<td>218</td>
<td>213</td>
<td>226</td>
</tr>
</tbody>
</table>

8 Quench resistor

The quench resistor ($R_Q$) was measured at room temperature and at −40°C. The mean $R_Q$ is 180 kΩ at 25°C for H2014 compared to 210 kΩ for H2015 (23% increase compared to H2014). Table 3 shows two values depending on the side of the H2015 detector (odd and even channels) with a spread of 10 kΩ. As for $V_{bd}$, $R_Q$ shows a structure that repeats itself on each die. This can be seen in Fig. 12 for odd and even channels of H2015 at 25 and −40°C. $R_Q$ increases by 6% between 25°C and −40°C for H2015 compared to 15% for H2014 (207 kΩ at −40°C).

![Figure 12: $R_Q$ for H2015 at 25°C on the left and −40°C on the right.](image)

9 Photo detection efficiency

Photo detection efficiency (PDE) is defined as the number of detected photons divided by the number of incident photons. PDE measurements were done on three different channels at three different $\Delta V$. H2014 is used as reference with 39% PDE for $\Delta V = 3.5$ V and at 475 nm. This measurement was corrected for cross-talk, AP, gain, DCR, temperature and surface increase (between H2014 and H2015). For H2015, the PDE peak is around 50% at $\Delta V = 3.5$ V and at 480 nm. PDE for H2015 at $\Delta V = 2.5$ V is the same as H2014 at $\Delta V = 3.5$ V (39%). For both detectors, the PDE peak is at 475 nm.

To cross check the results shown in Figs. 13, we measured the relative PDE by comparing the frequency of photons detected. This measurement uses a threshold on the single photon peak height and does not depend on the gain measurement. Since the measurement is not automated we use only two different wavelengths but several $\Delta V$. The results were corrected for DCR, delayed cross-talk and AP. The light intensity was adjusted sufficiently low to avoid random overlap of detected photons.

One can see that the PDE in Fig. 14 corresponds except at very low $\Delta V$ shown in Table 4. The 2% difference at $\Delta V = 3.5$ V can be explained by an under-estimated noise correction in the current measurement.
Characterisation of SiPM arrays

Figure 13: PDE for three channels at $\Delta V = 1.5, 2.5, 3.5$ and $4.5 \text{ V}$. The emission spectra of the SCSF-78 fibre as well as of a green emitting (NOL L191) fibre are overlaid. H2014 on the left and H2015 on the right.

Figure 14: PDE obtained through frequency measurements. H2014 and H2015 were measured at two different wavelength (peak PDE at 475nm and 650nm). H2014 at $\Delta V = 3.5 \text{ V}$ and 475nm was set at 39% as reference. The results were corrected for DCR, delayed cross-talk and AP.

Table 4: Comparison between PDE obtained through current and frequency measurements.

<table>
<thead>
<tr>
<th>$\Delta V \text{ [V]}$</th>
<th>1.5</th>
<th>2.5</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2015 (475nm) Freq</td>
<td>31%</td>
<td>40%</td>
<td>47%</td>
</tr>
<tr>
<td>H2015 (475nm) Current</td>
<td>25%</td>
<td>40%</td>
<td>49%</td>
</tr>
<tr>
<td>H2014 (475nm) Freq</td>
<td>26%</td>
<td>34%</td>
<td>39%</td>
</tr>
<tr>
<td>H2014 (475nm) Current</td>
<td>34%</td>
<td>39%</td>
<td></td>
</tr>
</tbody>
</table>
Figure 15: DCR curves for 128 channels of a detector after $6 \cdot 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$ at $-40^\circ\text{C}$.

Table 5: DCR before and after annealing for 5 different irradiation dose at $\Delta V = 3.5 \text{ V}$ for H2014

<table>
<thead>
<tr>
<th>Irradiation level [ n_{eq}/\text{cm}^2 ] $\Delta V = 3.5 \text{ V}$</th>
<th>Before annealing</th>
<th>After annealing</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \cdot 10^{11}$</td>
<td>9.5 MHz</td>
<td>4.5 MHz</td>
<td>2.1</td>
</tr>
<tr>
<td>$6 \cdot 10^{11}$</td>
<td>21 MHz</td>
<td>10.5 MHz</td>
<td>2.0</td>
</tr>
<tr>
<td>$12 \cdot 10^{11}$</td>
<td>43 MHz</td>
<td>21 MHz</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Table 6: DCR before and after annealing for 5 different irradiation dose at $\Delta V = 3.5 \text{ V}$ for H2015

<table>
<thead>
<tr>
<th>Irradiation level [ n_{eq}/\text{cm}^2 ] $\Delta V = 3.5 \text{ V}$</th>
<th>Before annealing</th>
<th>After annealing</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3 \cdot 10^{11}$</td>
<td>12.4 MHz</td>
<td>6.4 MHz</td>
<td>1.9</td>
</tr>
<tr>
<td>$6 \cdot 10^{11}$</td>
<td>26.0 MHz</td>
<td>13.2 MHz</td>
<td>2.0</td>
</tr>
<tr>
<td>$9 \cdot 10^{11}$</td>
<td>40.0 MHz</td>
<td>20.5 MHz</td>
<td>2.0</td>
</tr>
<tr>
<td>$12 \cdot 10^{11}$</td>
<td>62.5 MHz</td>
<td>29.9 MHz</td>
<td>2.1</td>
</tr>
<tr>
<td>$24 \cdot 10^{11}$</td>
<td>124.8 MHz</td>
<td>63.9 MHz</td>
<td>2.0</td>
</tr>
</tbody>
</table>

10 IV scans and DCR

DCR is obtained through current measurement:

$$f_{\text{DCR}} = \frac{I}{G \cdot e}$$  \hspace{1cm} (2)

where $I$ is the current, $G$ is the gain and $e$ is the elementary charge. IV scans allow a current measurement for a large range of $\Delta V$ (like in Fig. 15). Note that the results for H2015 are not corrected for direct cross-talk, in contrast to the H2014 results, and that all measurement are done at $-40^\circ\text{C}$. All results are expressed as DCR per channel. To compare with H2014, everything must be scaled down by a factor including:

- 8% larger channel area compared to H2014.
- Direct cross-talk depending on $\Delta V$.

DCR for $6 \cdot 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$ at $\Delta V = 3.5 \text{ V}$ for H2015 corrected for area (8%) and direct cross-talk (5% at $\Delta V = 3.5 \text{ V}$) gives a DCR of 11.5 MHz. This result is comparable to H2014 at the same neutron fluence. The
DCR reduction through annealing is the same for both technologies. Concerning radiation hardness, both detectors are equivalent. For both technologies, no channel died during the irradiation process at any neutron fluence.

### 10.1 Annealing process

DCR reduces when the silicon is annealed. Annealing will be done during the accelerator shutdowns, where the SiPMs could be warmed up to 20 – 30°C. H2015 detectors were warmed up to 35°C during ten days. H2014 had a similar annealing process. The noise is reduced by a factor 2 as shown in Table 6. DCR has a strong temperature dependence and is typically reduced by a factor of 2 every 10°C for H2014 and H2015. The temperature dependence of the DCR is shown in Fig. 16. The temperature interval $T_{1/2}$ which leads to a noise reduction by a factor $f_R = 2$ is derived from $f_R = 2(\Delta T/T_{1/2})$.

Saturation appears for DCR bigger than 100 MHz (only 104 pixels with a recovery time constant of 35ns for H2015 for example). This effect can be seen in Fig. 17.

To have a better understanding of the time characteristics for the annealing process, H2015 detectors after 6 and 12 · 10¹¹ n<sub>eq</sub>/cm<sup>2</sup> were measured every day during the week of annealing. The procedure shows a two exponential behaviour of the annealing as shown in Fig. 18.

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**Figure 16**: DCR as a function of $\Delta V$ at different temperatures for a detector irradiated at 6 · 10¹¹ n<sub>eq</sub>/cm<sup>2</sup> after annealing for H2014 (left) and H2015 (right).

**Figure 17**: DCR as a function of temperatures at different $\Delta V$ for a H2014 (left) and H2015 (right) detector irradiated to 6 · 10¹¹ n<sub>eq</sub>/cm<sup>2</sup> after annealing.
Figure 18: DCR as a function of time during the annealing process (35°C) for a H2015 detector irradiated to 6 \cdot 10^{11} \text{n}_{\text{eq}}/\text{cm}^2 (left) and 12 \cdot 10^{11} \text{n}_{\text{eq}}/\text{cm}^2 (right) (all H2015).

11 Light yield

Measurement of the light yield was done using either the VATA64 or the Spiroc read-out electronic. For the VATA64 all correlated noise is included (\(\tau_{\text{shaping}} > 500\text{ns}\)) but for the Spiroc it is only partially included (\(\tau_{\text{shaping}} = 67\text{ns}\)). A difference in light yield is expected depending on the read-out electronic used (this effect can be seen by comparing Fig. 19 and Fig. 20, Fig. 21).

Figure 19: Light yield comparison between H2014 and H2015 read-out with VATA64.

Fig. 19 shows a difference of 4.3 photons between H2014 and H2015. If the light yield are corrected for correlated noise:

- H2014 \(\Sigma_{\text{noise}}=19.7\%\) -> LY = 18.8 photons
- H2015 \(\Sigma_{\text{noise}}=15.9\%\) -> LY = 22.9 photons

This correspond to an PDE increase of 22% which is compatible to the 21% obtained in Chap.(9). An \(\Delta V\) scan was done with the Spiroc on both H2014 and H2015. Light yields can be seen in Fig. 20 and Fig. 21.
The main properties are:

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>H2014</th>
<th>H2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta V = 3.5V )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_{bd} ) at 25(^\circ)C</td>
<td>55.1V ± 300mV on chip</td>
<td>52.2V ± 200mV on chip</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>53.7mV/K</td>
<td>60mV/K</td>
</tr>
<tr>
<td>Gain area</td>
<td>2.75 ( \cdot ) 10(^6)</td>
<td>3.25 ( \cdot ) 10(^6)</td>
</tr>
<tr>
<td>Gain current</td>
<td>3.75 ( \cdot ) 10(^6)</td>
<td>3.6 ( \cdot ) 10(^6)</td>
</tr>
<tr>
<td>Direct cross-talk</td>
<td>17%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Delayed cross-talk</td>
<td>1.8%</td>
<td>5.5%</td>
</tr>
<tr>
<td>After-pulse</td>
<td>1.8%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Peak PDE</td>
<td>39%</td>
<td>47%</td>
</tr>
<tr>
<td>Max PDE wavelength</td>
<td>475nm</td>
<td>480nm</td>
</tr>
<tr>
<td>Light Yield</td>
<td>23.4 photons</td>
<td>27.7 photons</td>
</tr>
<tr>
<td>Mean RQ at 25(^\circ)C</td>
<td>170kΩ ± 1kΩ</td>
<td>210kΩ ± 5kΩ</td>
</tr>
<tr>
<td>Mean RQ at -40(^\circ)C</td>
<td>185kΩ ± 1kΩ</td>
<td>225kΩ ± 5kΩ</td>
</tr>
<tr>
<td>Recovery time</td>
<td>25ns</td>
<td>35ns</td>
</tr>
<tr>
<td>Long component (( \tau_2 )) at 25(^\circ)C</td>
<td>30ns</td>
<td>40ns</td>
</tr>
<tr>
<td>Short component (( \tau_1 )) at 25(^\circ)C</td>
<td>&lt;1ns</td>
<td>&lt;1ns</td>
</tr>
<tr>
<td>DCR, ( 6 \cdot 10^{11} ) n(_{eq} )/cm(^2), -40(^\circ)C</td>
<td>15.2 (12.6 corr.) MHz</td>
<td>15 (13.2 corr.) MHz</td>
</tr>
<tr>
<td>( T_{1/2} ) at 10(^\circ)C</td>
<td>10(^\circ)C</td>
<td>10(^\circ)C</td>
</tr>
</tbody>
</table>

Despite a large improvement regarding direct cross-talk compared to H2014, H2015 shows a large after-pulse and delayed cross-talk. PDE has increased significantly from 39% at \( \Delta V = 3.5V \) to more than 47%. The increase in PDE is confirmed by an increase of light yield. Note that the DCR corrected includes corrections for area differences and direct cross-talk. It is comparable after these corrections. The small differences can come from a longer annealing time for H2014. The right operation point regarding PDE and noise needs to be determined.
A Methods

A.1 Production test setup for breakdown computation

$V_{\text{bd}}$ is the most important property and has to be measured precisely. I-V curves cannot reach the necessary precision of $V_{\text{bd}}$. Computing the ADC gain in the light spectrum and extrapolating it to zero is the most precise way to determine it. A new light tight box has been developed that allows $V_{\text{bd}}$ measurement of 8 SiPM simultaneously. The features are:

- Short measurement time. Objective is less than 15 minutes for 8 detectors.
- Simple handling of detectors. This implies no screws to hold the detectors and easy access, for mounting and unmounting.
- Homogenous light injection system. The LHCb SciFi light injection system is used. It is based on scratched fibre that will distribute the photons over its length. The optical fibre will be coupled to a mat plexiglas piece to improve the light homogeneity.
- Constant temperature at 25°C. A heat spreader is put on the top of the SiPM to thermalise the detectors.

The read-out is done by using VATA64 chip [5]. A picture of the setup can be seen in Fig. 22.

The ADC gain computation (Fig. 23) and the extrapolation (Fig. 24) are done with a peak selection based algorithm. It allows a fast and precise way to determine $V_{\text{bd}}$ for all 128 channel for all 8 detectors.
A.2 Pulse shape, cross-talk and absolute gain measurement through an oscilloscope

An oscilloscope is used for pulse shape determination, cross-talk, after-pulse and gain measurement. The oscilloscope is 1GHz with an 2GHz bandwidth amplifier. The oscilloscope is used to measure the pulse shape and the time constant. Only one channel can be read out at a time. Channels are selected for the read out with a circuit. Waveforms are saved and analyse with a peak selection procedure that allows cross-talk and after-pulse detection. The recovery time is estimated with the signal amplitude of after-pulse. The fast time constant ($\tau_1$) is dominated by the acquisition bandwidth. The slow time constant ($\tau_2$) is estimated with the fit of the slow component. Recovery and long component can be seen in Fig. 25.

The oscilloscope can also be used to measure the absolute gain. As the signal for these detectors are very fast, part of the signal is filtered and therefore not accounted correctly in the VATA64 amplifier. The idea is to measure the gain by counting the number of pulses within a certain time. The same amplifier as for the pulse shape measurement is connected to the circuit. The signal is then analyse with the oscilloscope. For low thresholds, 1, 2 and more photon peaks will be detected. An LED can serves as a noise generator when set in a continuous mode. Knowing the number of counts, one can...
get the gain (not corrected for the cross-talk). The gain is given by:

$$G_I = \frac{I}{f_{pix} \cdot e}$$  \hspace{1cm} (3)

with $I$ the current, $e$ the elementary charge and $f_{pix}$ the firing frequency given by:

$$f_{pix} = \frac{\#counts\ 1PE}{time\ interval}$$  \hspace{1cm} (4)

The number of pulses in a 100 µs interval can be seen in Fig. 26. The gain obtained by this method is called gain current ($G_I$).

![Figure 26: Number of pulses in a 100 µs interval. Single photon pulses and double photon pulses can be seen. The threshold level counting the number of pulses above it is shown in red.](image)

An other way to measure the gain is by computing the area of the pulse. Histograms like in Fig. 27 are obtained, were the gain can be obtained by:

$$G_A = \frac{Q}{A \cdot e}$$  \hspace{1cm} (5)

with $A$ the gain of the amplifier and $e$ the elementary charge. $Q$ is given by:

$$Q = \int I dt = \int \frac{U}{R} dt$$  \hspace{1cm} (6)

The gain obtained by this method is called gain area ($G_A$).
A.3 I-V curves measurements with a multiplexer

A labview controlled multiplexer system allowing to measure I-V on mounted detectors was developed. The measurement is done on all 128 channels of a detector. I-V scans are used to obtain the breakdown voltage. To cool down detectors, a new developed cooling box is used. To reach -50°C without using a Peltier cell (Peltier induces noise on the detector), the air volume inside the cooling box was pushed to a minimum. This allows a $V_{bd}$ determination as a function of temperature and so the temperature dependence of the detector (temperature coefficient).

Figure 28: Multiplexer setup. Mounted SiPM is connected to the multiplexer. A cooling box is connected to a liquid chiller to reach temperatures down to -50°C.

I-V scans over the 128 channels and the $V_{bd}$ profile can be seen in Fig. 29 and Fig. 31. $V_{bd}$ can be found from I-V scans by plotting:

$$I \cdot \frac{dV}{dI}$$

(7)

The result of the derivative can be seen in Fig. 30. One can see a linear behaviour between 52.5V and 54V. $V_{bd}$ corresponds to the voltage where the linear fit crosses zero. Some continuous light can be
injected to increase the current and better the resolution. $V_{bd}$ obtained through I-V scans are less precise (uncertainty of $\sim \pm 100\text{mV}$) compared to the method expose in Chap.(A.1) but allows temperature scans.

![Figure 29: I-V scan in reversed bias region with multiplexer for 128 channels at 20°C.](image)

![Figure 30: $I \cdot \frac{dV}{dI}$ for 128 channels at 20°C. Linear region can be seen between 52.5 and 54V.](image)

Scanning in the forward region allows the measure of $R_Q$. The I-V curves are linear in this region. $R_Q$ is given by:

$$R_Q = N_{\text{pixel}} \cdot \frac{dV}{dI}$$

(8)

with $N_{\text{pixel}}$, the number of pixel. I-V scans for 128 channels in forward bias can be seen in Fig. 32. This setup is also used to measure DCR on cooled irradiated detector where homogeneity measurement requires a large number of channels.
A.4 PDE measurements

The photo detection efficiency measurement is done in a light tight box with a Xenon lamp used with a monochromator. The light output of the monochromator is coupled to an optical fibre going to a photo diode (PD) for calibration or to the SiPM. The wavelength set by the monochromator is controlled by a computer. As a reference, a 128 ch. Hamamatsu S10943-3183(x) device was used and its PDE is set at 39 % for $\Delta V = 3.5$ V at 475nm.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{setup.png}
\caption{Scheme of the PDE setup.}
\end{figure}

A schematic of the setup can be seen in Fig. 33. The PDE relative to a calibrated photodiode will be determined. The relative PDE can be calculated using equation (9).

\begin{equation}
\text{PDE}_{rel} = QE_{PD} \cdot \frac{I_{SiPM}}{I_{PD}} [7]
\end{equation}

The index PD stands for photodiode and $I_{SiPM}$, $I_{PD}$ respectively are the current of the SiPM and the photodiode. The current of the SiPM is corrected for cross-talk, after-pulse, gain, surface variations and dark current. $QE_{PD}$ is the quantum efficiency of the photo diode.
A.5 Irradiation

Detectors were irradiated with neutron in a nuclear reactor situated in Ljubljana. The spectral composition of the channel used is 37.9% thermal neutrons ($< 0.625\,\text{eV}$), 29.4% epithermal neutrons ($0.625\,\text{eV} - 0.1\,\text{MeV}$) and 32.7% fast neutrons ($> 0.1\,\text{MeV}$). The total neutron flux is $1.175 \cdot 10^{13}\,\text{n}_{\text{eq}}/\text{cm}^2/\text{s}$.

The neutron profile can be seen in Fig. 34. Channel TIC was used for the samples. There was no extra shielding.

Figure 34: Lethargy neutronspectrum in representative irradiation channels in core 189 of the TRIGA reactor. Normalisation per source neutron. Taken from [8].

The purpose of the irradiation is to measure the detector performance in the expected LHCb environment. For example, a dose of $6 \cdot 10^{11}\,\text{n}_{\text{eq}}/\text{cm}^2$ corresponds to the dose expected during the lifetime of the LHCb upgrade.

The irradiation increases the dark count rate (DCR). The DCR can be calculated from the measured current in an IV scan for all 128 channels (multiplexer):

$$DCR = \frac{I}{G \cdot e}$$  \hspace{1cm} (10)

with $I$ the current, $G$ the gain and $e$ the elementary charge. Typical DCR curves can be seen in Fig. 35. The DCR after irradiation can be reduced by annealing which consist to warm up the detectors. This annealing process could be performed during LHC shutdowns in order to increase the lifetime of the detectors.

A.6 Fibre modules

Detectors are attached to short scintillating fibre (SciFi) module to measure the light yield. The passage of a particle through a SciFi module produces light in several fibres which is collected in a certain number of SiPM pixels. Here the particle used are electrons, produced with and e-gun which is placed on the top of the fibre (Fig.(36). It is a $\beta$-spectrometer with a $\beta$-emitting 90 Sr source and a solenoid coil allowing to generate a magnetic field that selects the energy of the electrons. In addition, it is equipped with a trigger system which is composed of three 1 mm square plastic fibres coupled to two single channel SiPMs. The energy loss of the electrons in the trigger fibres is measured to be approximately 200 keV and their input kinetic energy in the fibre mat is approximately $E_{\text{kin}} = 1\,\text{MeV}$. Because of multiple scattering and angular tracks, electrons deposit energy over a larger zone than high energetic pions. The difference leads to an increased width of the clusters by typically 1 channel. Placed on an X-Y moving table, the electron-gun can scan the module at low and constant velocity which is convenient to check the homogeneity of the response of all read-out channels. It was therefore used to develop correction for non-uniformity.

This number of collected photons, called the light yield, is measured by applying a clustering algorithm to each particle passage event. In a first step, the raw data of all channels must be converted
into photo-electrons (p.e.) using the calibrated adc-gain. Then, the algorithm selects channels with signal above a specified seed threshold (3.5 p.e.). If several channels next to each other have signal exceeding the threshold, they form an entity that is called a cluster. To finalize it, the algorithm controls the first channel to the left and to the right of the cluster. If they have signal above the neighbour threshold (1.5 p.e.), they are included in the cluster. In the end, the cluster is considered as the actual passage of a particle if the total number of photoelectrons inside the cluster exceeds the sum threshold (4.5 p.e.). This figure is precisely the number of photons collected and by processing a large number of events, it leads to a measurement of the light yield. SiPMs are read out with the VATA64 or the Spiroc.

Figure 35: DCR curves for 128 channels of a $6 \cdot 10^{11} \text{n}_{\text{eq}}/\text{cm}^2$ detector at -40°C.

Figure 36: Scheme of the light yield setup.
References


[5] M.G.Bagliesi et al., A custom front-end ASIC for the readout and timing of 64 SiPM photosensors, Elsevier

